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EVALUATION OF HIGH-TEMPERATURE LUBRICANT UNDER CYCLIC OPERATING CONDITIONS

INTERIM REPORT
TFLRF No. 301

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13. ABSTRACT (Maximum 200 words)

The performance of a candidate high-temperature lubricant was determined under cyclic operating conditions of idle, maximum torque, and maximum power at intermediate and high oil temperatures. The results were compared with previous oil performance results obtained during steady-state, high-temperature operation.

Operation at the cyclic conditions resulted in approximately twice the piston top groove fill deposits. This result confirmed the need to include cyclic operation requirements in any future high-temperature lubricant specification.

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EXECUTIVE SUMMARY

Problems: Future engines for powering U.S. Army ground equipment are expected to require improved or even novel lubricants. Engine oil will be exposed to severe high-temperature environments. Current engine lubricant technology (MIL-L-2104F) is inadequate for future low-heat rejection (LHR) engine requirements. A methodology for defining high-temperature lubricant requirements needs to be developed.

Objective: Only high-temperature, steady-state diesel engine operation had been used in the development of new high-temperature lubricants. The objective of this project was to determine if cyclic operation needed to be included in the evaluation of high-temperature diesel engine lubricants.

Importance of Project: A key limiting technology in the development and fielding of future LHR engines for the U.S. Army is the ability of the engine oil to function at elevated temperatures. Requirements for high engine oil temperature exceed the ability of current generation oils in the areas of thermal/oxidative stability and low deposition rates. In addition to the high-temperature capability, the engine oil must function without loss of performance at low and intermediate oil temperatures encountered during cyclic operation.

Technical Approach: The performance of a candidate high-temperature lubricant was determined under cyclic operating conditions of idle, maximum torque, and maximum power at intermediate and high oil temperatures. The results were compared with previous oil performance results obtained during steady-state, high-temperature operation.

Accomplishments: Operation at the cyclic conditions resulted in approximately twice the piston top groove fill deposits. This result confirmed the need to include cyclic operation requirements in any future high-temperature lubricant specification.

Military Impact: Development of acceptable high-temperature lubricants will allow all the benefits of minimum-cooled diesel engines to be realized. The benefits include improved specific fuel consumption, increased vehicle power density, reduced engine size, and reduced cooling maintenance requirements.

FOREWORD/ACKNOWLEDGEMENTS

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The authors would like to acknowledge the assistance provided by Cummins Engine Company in supplying the candidate lubricant, and Mr. Scott Richards of SwRI in conducting the high-temperature engine tests.

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I. INTRODUCTION AND BACKGROUND

High-temperature lubricants (HTLs) were developed by Cummins Engine Company, with funding provided by U.S. Army Tank-Automotive Research, Development and Engineering Center (TARDEC).(1)* The HTLs were developed for use in a future, advanced, high-output diesel engine for heavy combat vehicles. Target oil sump temperature (OST) during lubricant development was 340°F (171°C).(1) During FY93, eight HTLs were evaluated in a 200-hour, steady-state, high-temperature L10 engine test at 340°F (171°C) OST. There is concern that HTL performance requirements must also be investigated under cyclic operating conditions that include transients of low and intermediate temperature. In previous Cummins/TARDEC work, a candidate HTL was found to have unacceptable deposition performance despite having excellent basestock oxidation stability. It was hypothesized that the deposits resulted from not operating this experimental product at a high enough temperature. In addition, it was suspected that cyclic operation may be even more severe for piston deposit formation. While lubricant evaluations at full output, maximum temperature are necessary to provide high-temperature oxidation and deposition protection, Army equipment will be operated at a variety of other conditions. It was essential that HTLs be evaluated at cyclic operating conditions that are representative of Army field operation.

II. OBJECTIVE AND APPROACH

The objective of this program was to determine the performance of a candidate HTL under cyclic operating conditions. A promising candidate HTL developed by Cummins Engine Company (1) was evaluated following a modified, tracked-vehicle test cycle (Federal Test Method 355). This cycle consists of alternating periods of idle, maximum torque, and maximum power and has been correlated to 4,000 miles of proving ground operations.(2)

* Underscored numbers in parentheses refer to the list of references at the end of this report.

III. MATERIALS

A. Lubricant

The candidate HTL, which contained a synthetic basestock, was designated Oil A-59 by Cummins. The summarized properties for Oil A-59 are presented in TABLE 1.

TABLE 1. Oil Properties for Oil A-59

K. Vis, cSt	
40°C	101.8
100°C	12.9
Viscosity Index	122
Sulfated Ash, wt%	1.1
TAN	3.3
TBN (D 4739)	9.3

B. Fuel

The test fuel was Howell RDF-7 "Mack" No. 2 diesel fuel. This was a custom-blended, controlled, research fuel containing 0.14 wt% sulfur. Typical fuel analyses for RDF-7 are presented in TABLE 2.

IV. EVALUATION

A. Engine

The test engine used was a modified 1991 Cummins L10-330E. A description of a stock L10-330E engine is presented in TABLE 3. The electronic control module (ECM) was modified by Cummins to enable operation at elevated oil and coolant temperatures and modified torque curve. A Cummins-type, dry sump oil system that included a modified oil pan was used. This system allowed continuous engine oil consumption measurements. A separate, isolated oil supply system was used for the turbocharger to eliminate potential turbocharger failure as experienced by Cummins in previous work. The turbocharger supplemental oil system was capable of 1.8 gal/min at 50 psig, and included an oil filter rated at 10 microns and a bypass circuit. Turbocharger oil inlet temperature was controlled to 220 ± 5°F (104 ± 2.8°C). The

TABLE 2. Properties for Test Fuel RDF-7

Property	Specification	Analysis	ASTM Test Method
Total Sulfur, wt%	0.10 to 0.15	0.14	D 2622
Gravity, °API	30 to 34	32.3	D 287
Hydrocarbon Composition			
Aromatics, vol%	42 to 47	45.6	D 5186
Olefins, vol%	Report	2.2	D 1319
Saturates, vol%	Report	52.2	D 1319
Cetane Index	40	40.2	D 4737
Copper Strip Corrosion	3 max	1	D 130
Flash Point, °F (°C)	125.6 (52) max	163 (73)	D 92
Cloud Point, °F (°C)	19.4 (–7) max	16 (–9)	D 2500
Carbon Residue on 10%			
Residium, wt%	0.20 max	0.12	(10% Bottoms)
Water and Sediment, vol%	0.05 max	<0.05	D 2709
Ash, wt%	0.002 max	0.001	D 482
K. Vis at 40°C, cSt	1.9 to 4.1	2.7	D 445
Distillation, °F (°C)			
Initial Boiling Point		360 (182)	D 86
10%		424 (218)	D 86
50%	475 to 550	491 (255)	
	(246 to 288)		D 86
90%	550 to 601	597 (314)	
	(288 to 316)		D 86
End Point	660 (349) max	642 (339)	D 86

TABLE 3. Engine Specifications for the Cummins L10-330E Engine

Engine Type:	Four-cycle, direct injection, turbocharged, aftercooled, compression ignition
No. of Cylinders:	6, in-line arrangement
Displacement, liters (in.^{3}):	10 (611)
Bore × Stroke, mm (in.):	125 × 136 (4.921 × 5.354)
Compression Ratio:	16.3 to 1
Rated Power, kW (BHP):	246 (330) at 1,600 rpm
Rated Torque, Nm (ft-lb):	1,695 (1,250) at 1,200 rpm

turbocharger oil system (pressure and temperature) was also tied into the ECM and safety shutdown systems.

Engine coolant was 100-percent propylene glycol and was used to achieve the required elevated 275°F (135°C) coolant temperature. This allowed engine oil sump to be heated to 340°F (171°C) without external heat supply.

The evaluations were conducted in a Southwest Research Institute (SwRI) test cell equipped with a 500-BHP, Midwest magnetic dynamometer. This dynamometer is capable of continuous steady-state operation or cyclic operation, excluding motoring capability, with controlled speed and load ramping. The test cell was equipped with closed loop cooling systems for the engine lube oil, fuel, intake air, coolant, and air-to-water aftercooler. The lube oil cooling system was of stainless steel construction.

The following parameters were controlled with closed loop control systems:

- rpm
- torque
- water outlet temperature
- fuel inlet temperature
- inlet air temperature
- intake manifold temperature
- oil sump temperature
- inlet air restriction
- turbo oil supply temperature.

The following parameters had electronic safety systems to provide for automatic engine shutdown in the event of a system failure or malfunction:

- speed
- torque
- water outlet temperature
- water outlet pressure
- oil temperature
- oil pressure
- turbo oil supply temperature
- turbo oil supply pressure
- oil system volume.

TABLE 4 lists the parameters and data units that were recorded on an hourly basis.

TABLE 4. Parameters

Parameter	Units
1. Speed	rpm
2. Torque	ft-lb
3. Calculated BHP	ft-lb/s
4. Fuel rate	HP
5. Calculated BSFC	lb/BHP-hr
6. Fuel inlet temperature	°F
7. Inlet air temperature	°F
8. Compressor air outlet temperature	°F
9. Aftercooler/intake manifold temperature	°F
10. Oil rifle/gallery temperature	°F
11. Oil pan/sump temperature	°F
12. Coolant pump inlet temperature	°F
13. Coolant pump outlet temperature	°F
14. Turbo oil supply temperature	°F
15. Individual cylinder exhaust temperatures, Cylinder Nos. 1-6	°F
16. Pre-turbo exhaust temperature – front	°F
17. Pre-turbo exhaust temperature – rear	°F
18. Exhaust stack temperature	°F
19. Fuel rail pressure	psig
20. Oil filter inlet pressure	psig
21. Oil filter outlet pressure	psig
22. Turbo oil supply pressure	psig
23. Oil rifle/gallery pressure	psig
24. Coolant pump inlet pressure	psig
25. Coolant pump outlet pressure	psig
26. Intake air restriction pressure (vacuum)	in. H_2O
27. Compressor outlet pressure	in. H_2O
28. Aftercooler/intake manifold pressure	in. H_2O
29. Pre-turbo exhaust pressure – front	in. H_2O
30. Pre-turbo exhaust pressure – rear	in. H_2O
31. Exhaust stack pressure	in. H_2O
32. Crankcase pressure	in. H_2O
33. Barometer	in. H_2O
34. Test cell air wet/dry bulb temperature	°F
35. Test cell air dewpoint temperature	°F
36. Oil consumption – continuous	lb/hr

Figure 1 shows the engine test cell installation.

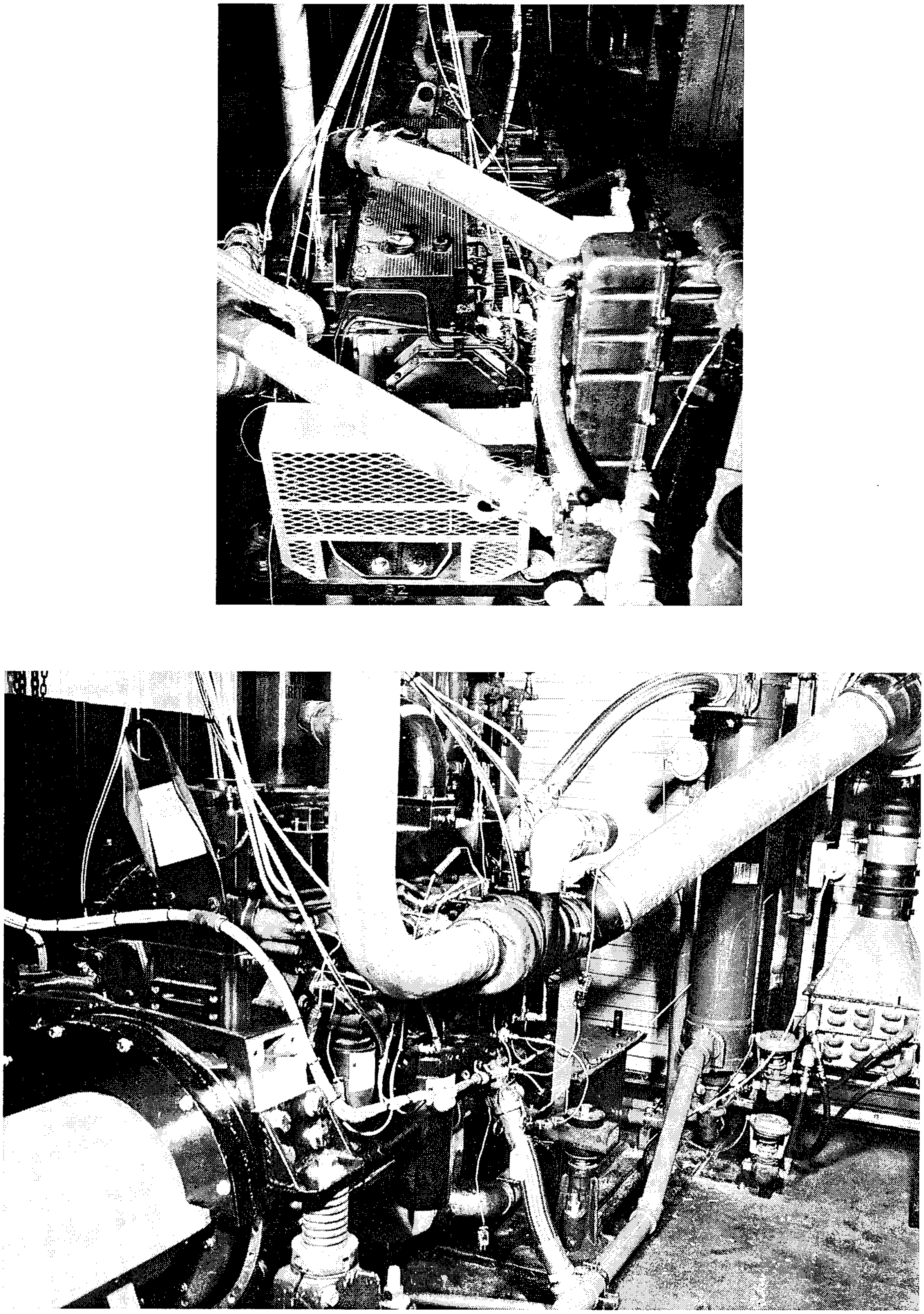


Figure 1. Engine test cell installation

B. Test Cycle

A modified version of the U.S. Army 240-hour, tracked-vehicle test cycle (TVTC) was used. TABLE 5 lists the three operating modes of the modified TVTC.

TABLE 5. Operating Modes of the Modified TVTC

	Mode I Idle	Mode II Rated Power	Mode III Peak Torque
Speed, rpm	800	1,600	1,200
Fuel Rate, kg/hr (lb/hr)	0.04 (0.08)	49 (107)	45 (100)
Power, kW (BHP)	0	246 (330)	213 (286)
Torque, Nm (ft-lb)	0	1,470 (1,083)	1,696 (1,250)

The previous evaluations conducted for Cummins were 200 hours of only Mode III steady-state operation. Oil sump and coolant out temperatures and the modified, cyclic 240-hour test procedure are presented in TABLE 6.

TABLE 6. The Modified TVTC Procedure

Step	Time, hr	Mode	Oil Sump Temperature	Coolant Out Temperature	Cumulative Time, hr
1	0.5	I (Idle)	Full cooling*	190°F (88°C)**	0.5
2	2.0	II (Power)	250°F (121°C)	190°F (88°C)	2.5
3	0.5	I (Idle)	Full cooling	190°F (88°C)	3.0
4	2.0	III (Torque)	340°F (171°C)	275°F (135°C)	5.0
5	*Repeat Steps 1-4 four times.*				20
6	4.0		Soak engine, shut off		
7	*Repeat Steps 1-6 twelve times.*				240

* Control system placed in maximum cooling position.
** Simulates thermostat operation.

The specifications for actual test conditions are presented in TABLE 7. In addition to the temperature variations from the standard TVTC, the 120-hour oil change was eliminated to further increase test severity.

TABLE 7. Test Condition Specifications

Control Point	Mode I (Idle)	Mode II (Power)	Mode III (Torque)	Tolerance
Speed, rpm	800	1,600	1,200	± 5 (2.8)
Torque, Nm (ft-lb)	0	1,469 (1,083)	1,696 (1,250)	±20 (11.2)
Oil sump, °F (°C)	Full cooling	250 (121)	340 (171)	± 5 (2.8)
Coolant outlet, °F (°C)	190 (88)	190 (88)	275 (135)	± 5 (2.8)
Intake manifold, °F (°C)	95 (35)	150 (66)	110 (43)	± 5 (2.8)
Intake air, °F (°C)	95 (35)	95 (35)	95 (35)	± 5 (2.8)
Inlet fuel, °F (°C)	104 (40)	104 (40)	104 (40)	± 5 (2.8)
Inlet air restriction, kPa (in. H_2O)	N/A	0.1 (0.5)	2.5 (10)	± 1 (0.6)
Exhaust back pressure, kPa (in. Hg)	N/A	1.7 (0.5) max	1.7 (0.5) max	N/A
Fuel rate, kg/hr (lb/hr)	N/A	49 (107)	45 (100)	

C. Discussion

Test 001 was initiated using Oil A-59, following the modified TVTC described in the previous section (TABLES 6 and 7). At 21 test hours, the engine was shut down due to high crankcase pressure. Improper crankcase thrust washer installation resulted in scuffing on Cylinder No. 3. The test was terminated at this point and the engine was rebuilt. The damaged parts that were replaced included the crankshaft, main and connecting rod bearings, and a cylinder kit. An SwRI test report for Test 001 is included as Appendix A.

Test 002 was conducted using Oil A-59, following the modified TVTC. This evaluation completed the scheduled 240 test hours without the normal 120-hour oil change. Oil filter plugging caused the bypass differential pressure to be reached at 160 hours. The filter was replaced and the test completed without additional filter plugging. This phenomenon occurred at 120 hours during the Cummins 200-hour, steady-state test. Cummins reported that the filter plugging was caused by a sludge-like material believed to be related to the additive package.

The plugging occurred when the lubricant had little soot or oxidation.(1) An SwRI test report for Test 002 is included as Appendix B. Summarized operating conditions for the maximum power and maximum torque modes are presented in TABLE 8, which indicate the test was conducted at the desired conditions. Discreet oil consumption measurements were made at 20-hour intervals throughout the test and are plotted in Fig. 2. Most of the oil consumption points fall between 0.05 and 0.09 kg/hr (0.1 and 0.2 lb/hr), with three points at 0.14 to 0.18 kg/hr (0.3 to 0.4 lb/hr). Overall average oil consumption for the test was 0.093 kg/hr (0.204 lb/hr). A moderate increase (62 percent) in kinematic viscosity at 212°F (100°C) was observed during the test, as shown in Fig. 3. The plots of copper, iron, and lead wear metals accumulated during the test, as determined by X-ray fluorescence, are presented in Fig. 4. The end-of-test wear metal level was indicative of at least moderate engine distress. As shown by Fig. 5, reserve alkalinity depletion was severe. The total base number (TBN) (D 4739) was reduced to less than 1.0 by 60 test hours.

After test completion, the engine was disassembled, inspected, and parts were rated for deposits and distress using standard Coordinating Research Council procedures. Detailed ratings are shown in Appendix B. Figure 6 shows the percent top groove fill for the six pistons and the overall average of 52.5 percent. One top ring was 90-percent hotstuck (Cylinder No. 4). Piston deposits expressed as total weighted demerits (TWD) are presented in Fig. 7. The average TWD for the six pistons was 1,781. Figure 8 shows the percent of liner crosshatch remaining in the ring travel area, while Fig. 9 shows the percent of heavy polish in the ring travel area of the liners. Cylinder No. 3 had the heaviest polish at 18.5 percent, while the overall six-cylinder average was only 6.3 percent.

The summarized six-cylinder average of the wear measurements for the 240-hour evaluation is shown in TABLE 9. Complete wear measurements are given in Appendix C. The wear measurements show small piston ring end gap increases for the test, and as expected, the top ring reveals the greatest ring gap change. The corresponding piston ring ratings revealed some discoloration on the middle ring of Cylinder No. 3 and the top ring of Cylinder No. 5, but overall, no apparent ring face distress was noted.

TABLE 8. Summarized Operating Conditions, Test 002

Parameter	Mode II (Power) Min	Mode II (Power) Max	Mode II (Power) Avg	Mode III (Torque) Min	Mode III (Torque) Max	Mode III (Torque) Avg
Speed, rpm	1599	1602	1600	1199	1202	1200
Torque, Nm (ft-lb)	1412 (1041)	1468 (1082)	1438 (1060)	--	--	--
Power, kW (BHP)	236 (317)	245 (329)	241 (323)	155 (208)	211 (283)	204 (274)
Fuel Rate, kg/hr (lb/hr)	46.4 (102.2)	49.8 (109.9)	48.6 (107.1)	42.1 (92.8)	44.2 (97.4)	43.2 (95.2)
Temperatures, °F (°C)						
Coolant Out	189 (87)	191 (88)	190 (88)	274 (134)	279 (137)	275 (135)
Coolant In	176 (80)	180 (82)	177 (81)	259 (126)	263 (128)	260 (127)
Oil Gallery	271 (133)	281 (138)	273 (134)	335 (168)	347 (175)	342 (172)
Oil Sump	274 (134)	280 (138)	275 (135)	312 (156)	342 (172)	339 (171)
Pressures						
Oil Gallery, kPa (psig)	377 (40)	425 (47)	412 (45)	315 (31)	412 (45)	356 (37)
Crankcase, kPa (in. H_2O)	1.7 (6.8)	3.2 (13.0)	2.5 (10.1)	1.3 (5.2)	3.5 (14.1)	2.0 (8.2)

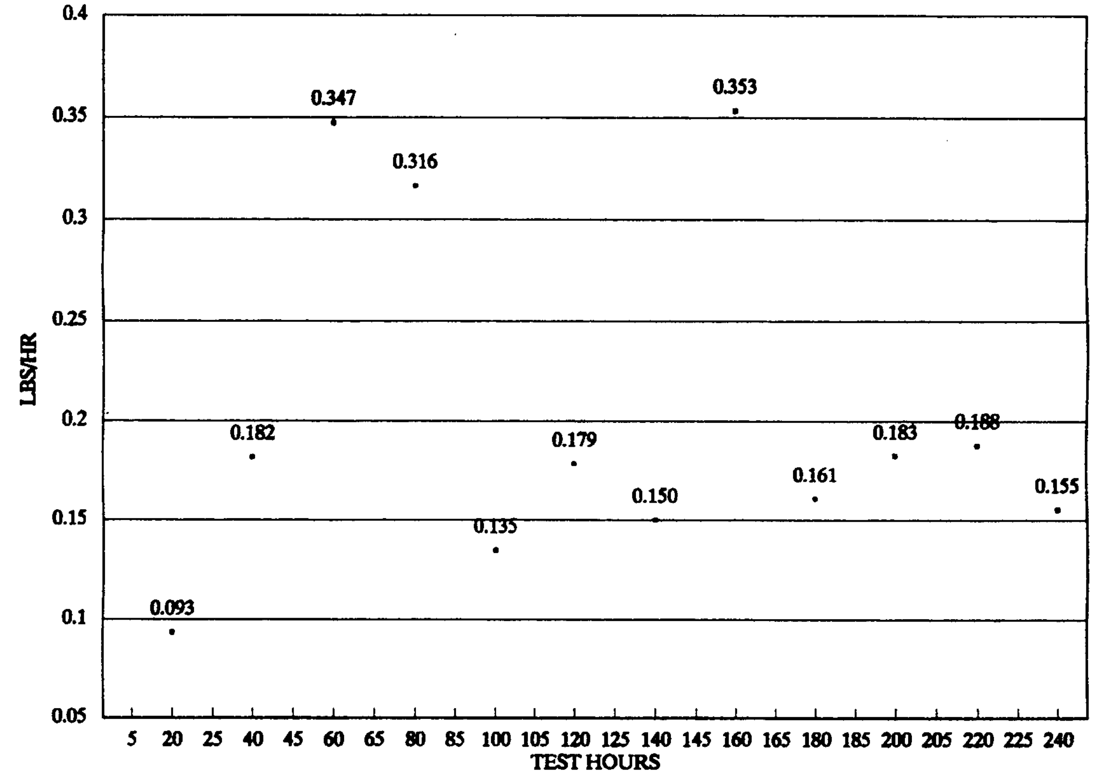


Figure 2. <u>Oil consumption, high-temperature L10 test for Oil A-59</u>

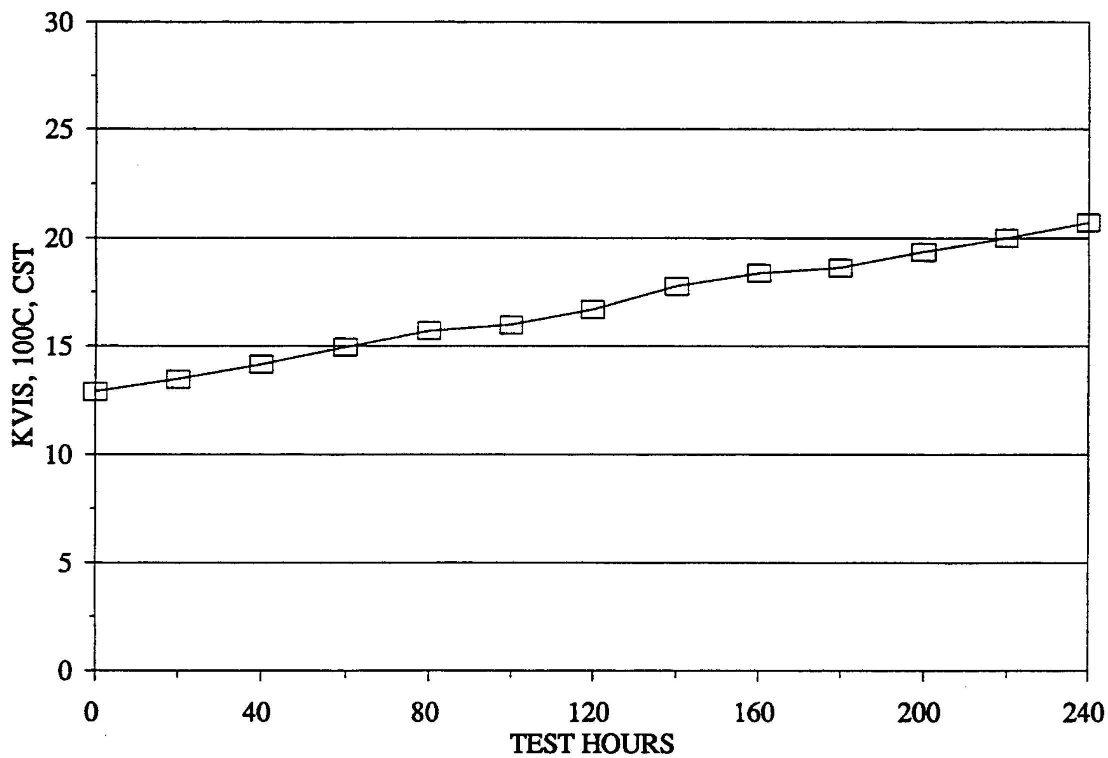


Figure 3. <u>Kinematic viscosity increase for Oil A-59</u>

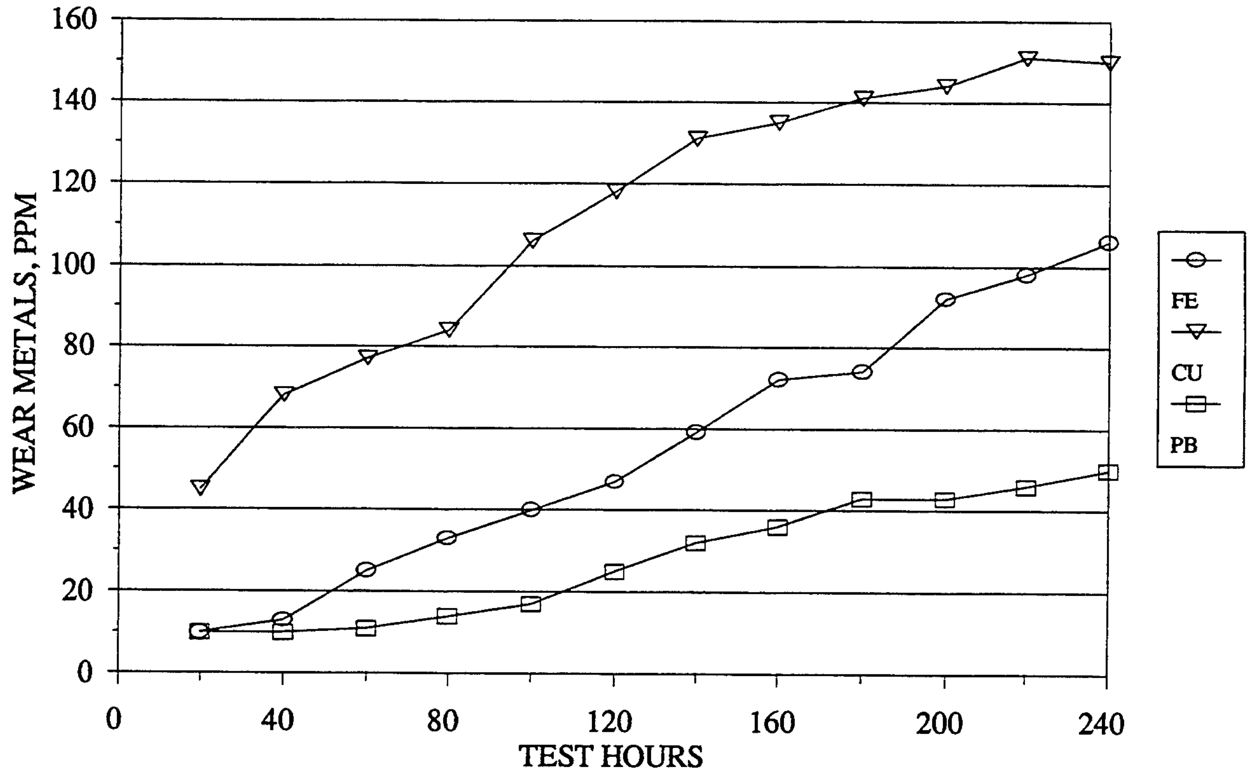


Figure 4. Wear metals for Oil A-59

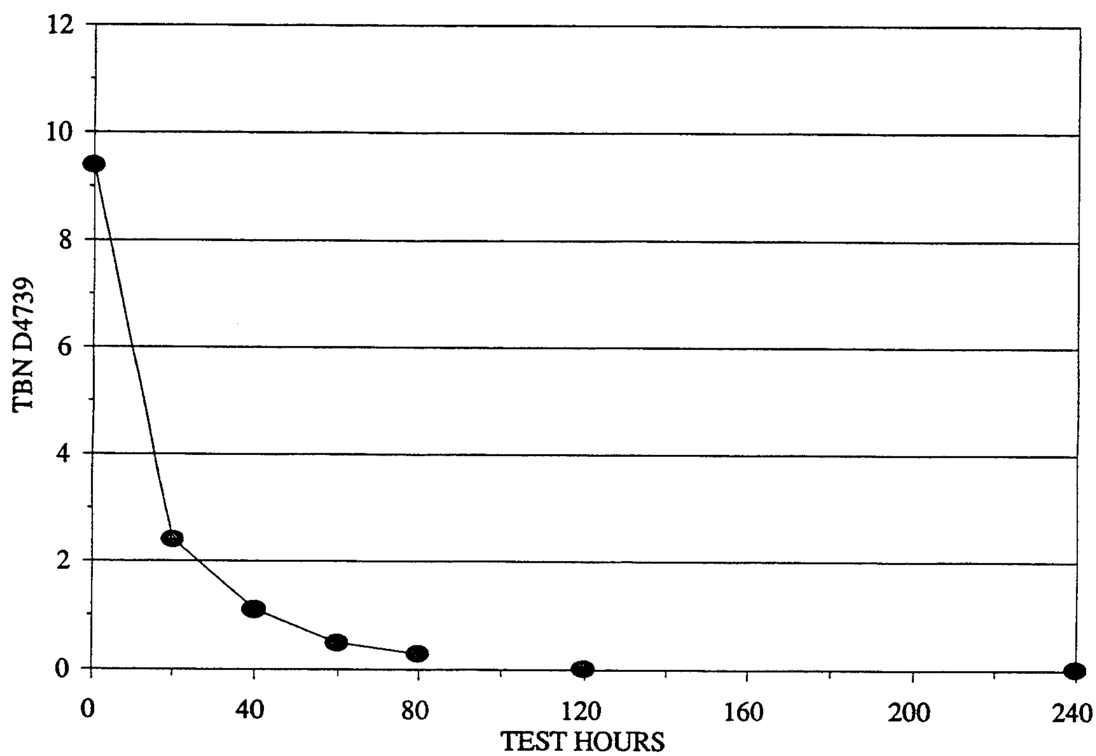


Figure 5. TBN depletion for Oil A-59

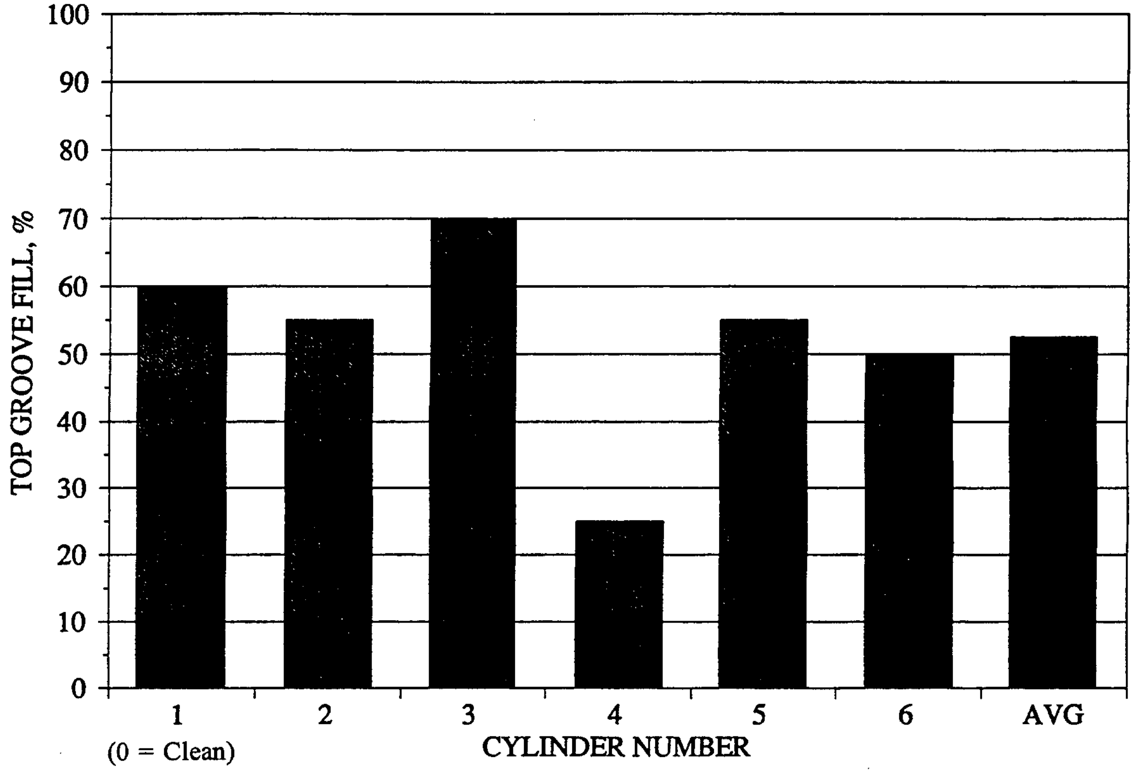


Figure 6. <u>Top groove fill for Oil A-59</u>

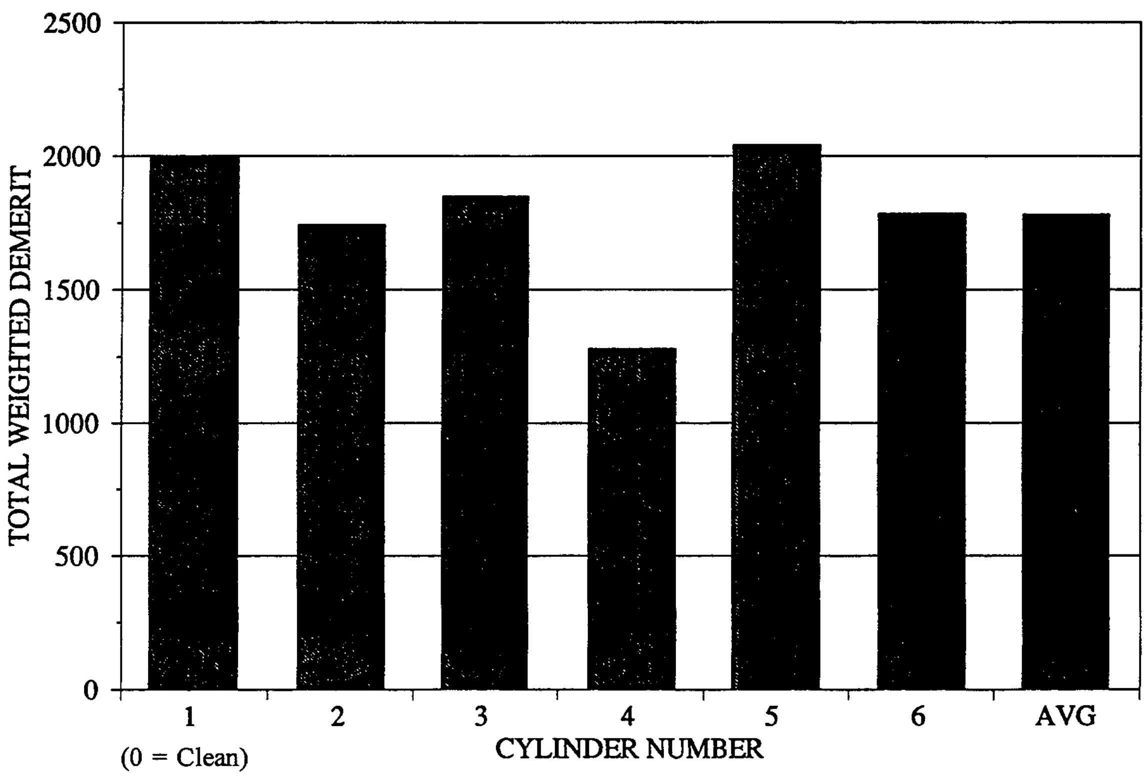


Figure 7. <u>TWD for Oil A-59</u>

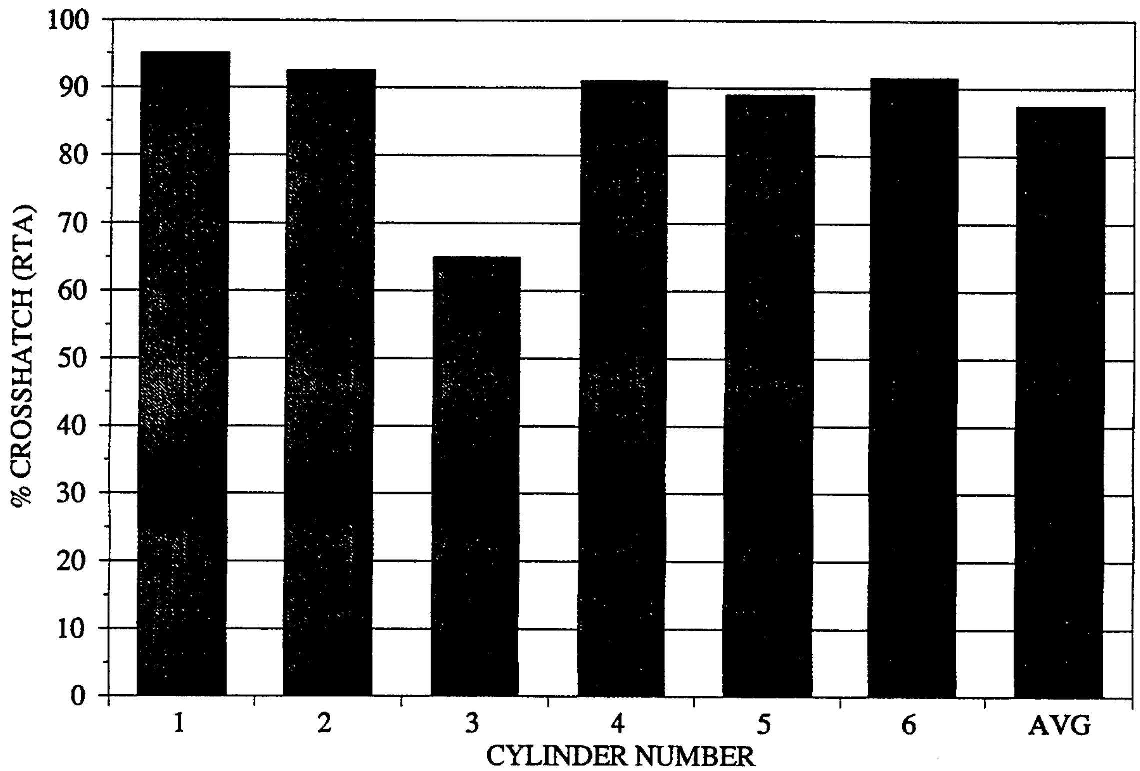


Figure 8. <u>Liner crosshatch remaining for Oil A-59</u>

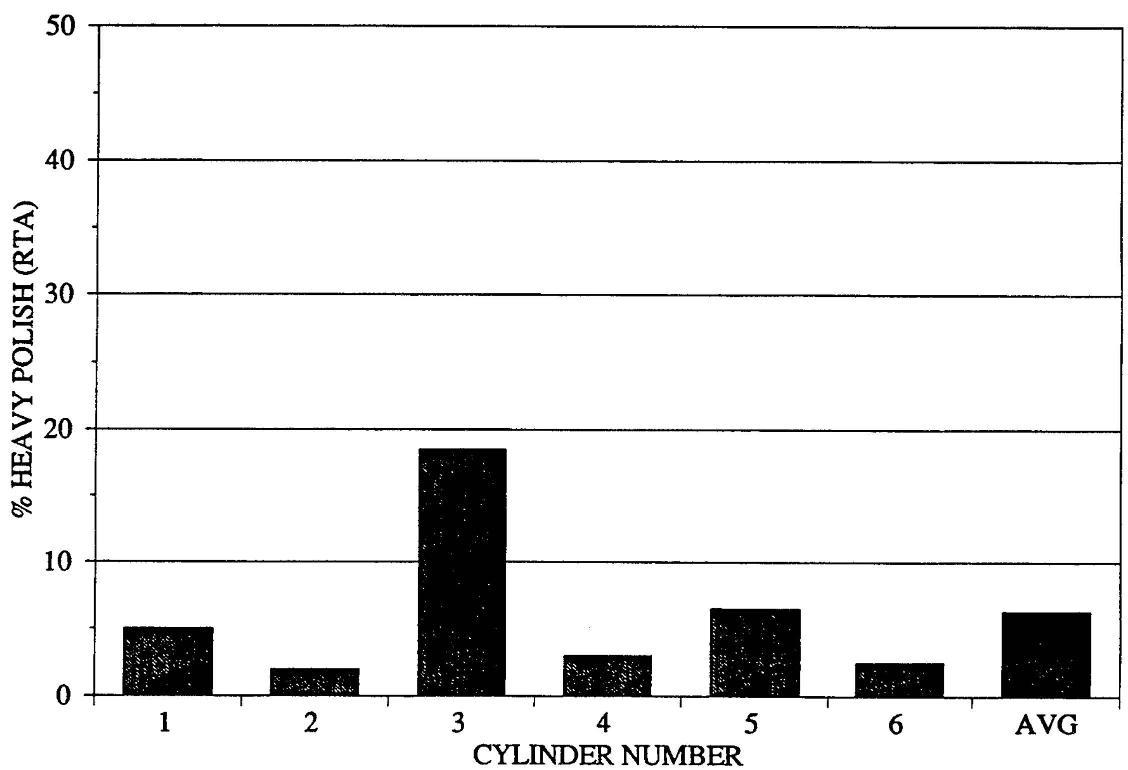


Figure 9. <u>Liner heavy polish for Oil A-59</u>

TABLE 9. 240-Hour High-Temperature Lubricant Evaluation Engine Component Average Dimensional Changes

Piston Ring End Gap Change, in.	
Top Ring	0.003
Intermediate Ring	0.001
Oil Ring	0.002

Piston Pin-to-Bushing Clearance Change, in.

	Articulated Crown	Articulated Skirt	Connecting Rod
Vertical	0.0013	0.0003	–0.0002
Horizontal	–0.0004	0.0002	–0.0002

Installed Cylinder Liner Diameter Change, in.	
Front-to-Back	–0.0005
Left-to-Right	0.0005
Overall	0.0000

Bearing Weight Loss, mg

Connecting Rod		Main	
Lower	7.2	Lower	58.4
Upper	206.3	Upper	32.1

Bearing Journal and Bearing Shell Clearance Change, in.

Connecting Rod	Main
0.0135	–0.0004

The piston pin-to-bushing clearance variations revealed some interesting results. The measurement for the piston pin to articulated crown bushing revealed an increase in the vertical clearance and a decrease in the horizontal clearance. This would indicate an ellipsoidal shape of the crown bushing, with wear along the cylinder axis, and most likely, deposit buildup on the thrust axis. The piston pin-to-articulated skirt measurement revealed minimal clearance changes for the test. The measurements for the piston pin to connecting rod bushing reveal a slight

decrease in clearance, but the values are most likely within the accuracy of the measurements. However, the visual connecting rod piston pin bushing ratings revealed considerable bushing distress in the vertical direction, with an average of 75-percent exposed copper for the engine. The discrepancy between the dimensional and subjective visual ratings of the connecting rod piston pin bushing (shown in Appendix C) could possibly be attributed to slight lubricant deposition on the bushing.

The average installed cylinder liner diameter changes indicate very little liner wear occurred, corresponding with the visual ratings discussed previously that indicated minimal bore polish and cylinder liner distress.

The bearing weight loss and bearing journal-to-bearing shell clearance changes indicate more wear occurred on the connecting rod bearings than the main bearings. The upper half of the connecting rod bearing revealed substantially greater average weight loss for the engine compared to the other bearing shells. As expected, minimal weight loss occurred for the lower connecting rod bearing shell. Not anticipated, however, was how consistent the main bearing upper and lower shell weight loss appeared; the lower main bearing shells were expected to reveal substantially greater weight loss than the upper shells. The journal-to-shell clearance variations for the test reveal that the connecting rod bearing weight loss is manifested in an increased clearance and indicates a minimal change in the main bearing clearances. The average component dimensional variation results indicate the connecting rod bearing shells are a critical component in the L10 engine.

A hardware review of L10 engine components is included as Appendix C. The hardware review consists of subjective visual evaluations of various engine parts, including overhead and valve train components. Overall, the valve train and overhead revealed some play in the cam roller follower axles, abnormal wear on several injector push rod sockets, substantial wear scars on rocker lever shafts, polished valve lever bushings, severe wear and pitting on injector lever bushings, and abnormal wear on several injector link balls. Several of the bearing shells and bushings throughout the engine displayed evidence of corrosive attack around the oil feed holes.

TABLE 10 contains the 240-hour, end-of-test used oil analyses. The used oil generally had moderate to severe degradation. Viscosity, acid and base numbers, insolubles, and wear metals all indicated that the oil was substantially degraded and that an oil change was needed.

TABLE 10. Used Oil Properties
(Oil A-59, Test 002, 240 Hours)

Property	Value	New Oil	Change
K. Vis, cSt			
40°C	191.75	101.8	+89.95
100°C	20.86	12.9	+ 7.96
Viscosity Index	129	122	+ 7
High-Temperature, High-Shear Viscosity, 150°C, cp (D 4624)	6.08	ND*	--
Sulfated Ash, wt%	1.35	1.1	+ 0.25
TAN	6.3	3.3	+ 3
TBN (D 4739)	0.0	9.3	− 9.3
Insolubles, wt%			
Pentane A	4.76		
Toluene A	0.05		
Pentane B	3.50		
Toluene B	1.00		
Soot, wt%, TGA	2.3		
Elements, ppm (ICP)**			
Ca	3335		
Mg	23		
P	5512		
Zn	1037		
Al	5		
B	<1		
Cr	4		
Cu	216		
Fe	145		
Na	4		
Pb	72		
Si	29		
Sn	9		
Elements, ppm (XRF)†			
Cu	150		
Fe	106		
Pb	50		

* ND = Not determined
** ICP = Inductively Coupled Plasma spectroscopy
† XRF = X-ray Fluorescence spectroscopy

A comparison of the results of cyclic (240-hour) and steady-state (200-hour) evaluations of Oil A-59 is presented in TABLE 11. The thermal loading on the lubricant was greater in the steady-state test with 200 continuous hours at 340°F (171°C) OST as compared to the cyclic test that operated 96 non-continuous hours at 340°F (171°C) and 96 non-continous hours at 275°F (135°C) OST. The higher thermal loading in the steady-state test contributed to a lubricant viscosity

TABLE 11. Comparison of Cyclic and Steady-State Tests (Oil A-59)

Parameter	Cyclic Test	Steady-State Test
Total Test Hours	240	200
At 340°F (171°C) oil sump at 1,200 rpm	96	200
At 275°F (135°C) oil sump at 1,600 rpm	96	0
At idle at 800 rpm	48	0
Oil Consumption Rate, lb/hr	0.204	0.198
Deposits		
Average top groove fill, %	52.5	19.8
Average piston TWD	1,781	1,912
Average crownland carbon	2.0	0.8
Wear and Distress		
Push tube tips	Several w/wear	Several w/seizure
Bearing distress	75% Cu rod bush	
Used Oil Properties (EOT)*		
K. vis, % increase		
40°C	88	195
100°C	62	128
Soot, wt%	2.3 (TGA)**	2.8 (IR)†
TAN	6.3	7.3
TBN (D 4739)	0.0	0.3
Elements, ppm (ICP)		
Fe	145	391
Cu	216	217
Pb	72	118
Oil Filter Plugging Test Hours	160	120

* EOT = End of test
** TGA = Thermogravimetric analysis
† IR = Infrared spectroscopy

increase that was approximately twice that observed in the cyclic test, at similar used oil soot levels. Oil consumption rates were similar for the two tests.

Average piston deposit TWDs were slightly more severe with the steady-state test. However, much heavier average top groove fill (52.5 percent) was observed with the cyclic procedure compared to the steady-state test (19.8 percent). Excessive top groove fill can lead to top ring sticking and/or wear and resulting performance loss. Also, average crownland carbon was slightly heavier in the cyclic test.

V. CONCLUSIONS

The following conclusions are offered:

- Piston top groove fill was 2.6 times more severe with the cyclic operation. One top ring was 90-percent hotstuck. Better top groove fill deposit control is needed for future HTL candidates.

- Oil viscosity at 100°C increased 62 percent during the cyclic test.

- Reserve alkalinity (TBN) was severely depleted by 60 test hours. Better TBN retention is needed.

- Used oil was substantially degraded as evidenced by high TAN and wear metals.

- Oil filter plugging occurred at 160 hours.

- Substantial wear or distress was observed in the following areas:
  - articulated piston crown piston pin bushings;
  - connecting rod piston pin bushing;
  - connecting rod upper bearing shell;

- cam roller follower axles;
- injector push rod sockets and corresponding injector link balls;
- rocker lever shafts;
- valve and injector lever bushings.

- Corrosive attack was observed on bearings and bushings.

VI. RECOMMENDATIONS

It is recommended that cyclic operation be included in any future HTL specifications. Piston top groove fill, potential ring sticking, and various wear-related distress were demonstrated with the cyclic operation. A new test cycle should be developed as the 240-hour cyclic conditions used may not have sufficient oxidative stress. Candidate HTLs with improved deposition and antiwear characteristics are needed.

VII. LIST OF REFERENCES

1. Wang, J.C. and M.G. Sublette, "High-Temperature Liquid Lubricant Development, Part I: Engine Tests," SAE Paper No. 932842, 1993.

2. Coordinating Research Council, Inc., "Development of a Military Fuel/Lubricant/Engine Compatibility Test," Final Report, Atlanta, GA, January 1967.

APPENDIX A

Cummins L10 High-Temperature Cyclic Test
Test No. 001

SOUTHWEST RESEARCH INSTITUTE
San Antonio, Texas

DIVISION OF
AUTOMOTIVE PRODUCTS AND EMISSIONS RESEARCH

Report on

a

CUMMINS L10 HIGH TEMPERATURE TEST

Conducted for

BELVOIR FUELS AND LUBRICANTS RESEARCH FACILITY

A 59

Engine No. 001
Test No. 001

I certify that this evaluation was conducted, to the best of my knowledge, in accordance with the conditions specified in Cummins L10 High Temperature Test Procedure, supplemented by information letters and/or contact with the appropriate test procedure sponsor.

Scott M. Richards
Senior Research Engineer
Department of Gasoline
and Diesel Engine
Lubricants

October 22, 1993

CUMMINS L10-HTT (1200 RPM)
OPERATIONAL SUMMARY

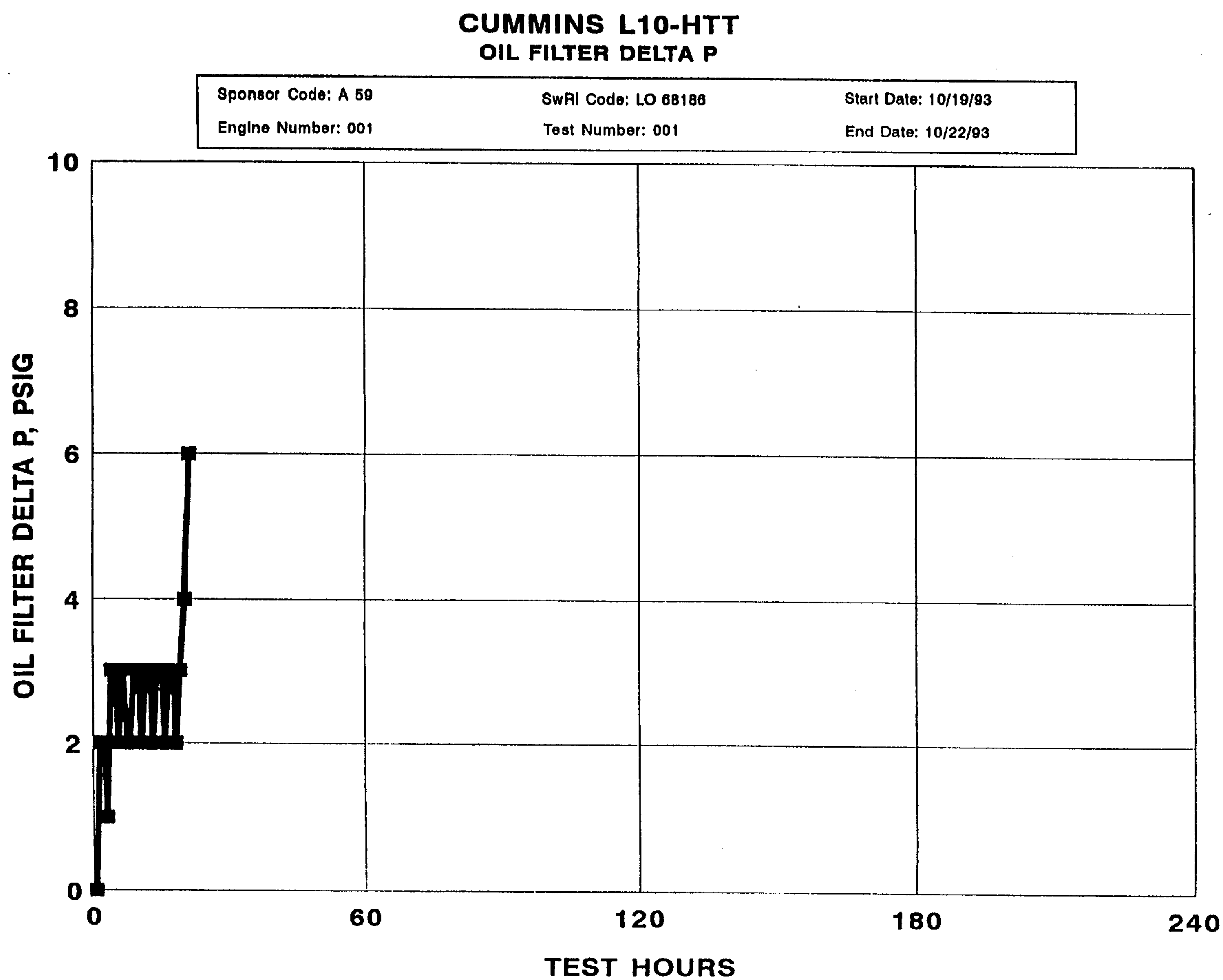
Sponsor Code: A 59	SwRI Code: LO 68186	Start Date: 10/19/93
Engine Number: 001	Test Number: 001	End Date: 10/22/93

		MINIMUM	MAXIMUM	AVERAGE
SPEED	(RPM)	1195	1199	1197
TORQUE	(FT*LB)	1119.0	1199.0	1177.8
POWER	(BHP)	270.8	276.8	274.6
FUEL RATE	(LB/HR)	96.4	98.1	97.4
TEMPERATURES (°F)				
COOLANT OUT		276	276	276
COOLANT IN		258	262	260
OIL GALLERY		341	343	342
INTAKE AIR		90	97	94
OIL SUMP		339	341	340
TURBO OIL SUPPLY		112	143	122
AFTERCOOLER COOLANT INLET		61	83	69
AFTERCOOLER COOLANT OUTLET		98	100	99
FUEL		104	105	104
INTAKE MANIFOLD		114	116	115
COMPRESSOR OUTLET		333	340	337
PUMP OUTLET COOLANT		258	260	260
AMBIENT		95	115	101
EXHAUST FRONT MANIFOLD		1287	1295	1292
EXHAUST REAR MANIFOLD		1181	1200	1189
EXHAUST CYLINDER #1		1156	1260	1188
EXHAUST CYLINDER #2		1230	1245	1238
EXHAUST CYLINDER #3		1208	1214	1210
EXHAUST CYLINDER #4		1215	1233	1225
EXHAUST CYLINDER #5		1260	1279	1270
EXHAUST CYLINDER #6		1182	1197	1188
EXHAUST AFTER TURBO		975	986	981
PRESSURES				
FUEL RAIL	(PSIG)	156	156	156
OIL FILTER IN	(PSIG)	56	57	56
OIL FILTER OUT	(PSIG)	53	54	53
OIL FILTER DELTA	(PSIG)	3	4	3
OIL GALLERY	(PSIG)	36	37	36
WATER PUMP INLET	(PSIG)	12	13	12
WATER PUMP OUTLET	(PSIG)	22	23	23
COMPRESSOR OUTLET	(IN Hg, ABS)	73.6	75.8	74.4
INTAKE MANIFOLD BOOST	(IN Hg, ABS)	72.3	73.8	73.0
EXHAUST BACK PRESSURE	(IN Hg, GAGE)	0.0	0.1	0.1
EXHAUST MANIFOLD FRONT	(IN Hg, ABS)	55.5	56.4	56.1
EXHAUST MANIFOLD REAR	(IN Hg, ABS)	56.8	57.8	57.4
CRANKCASE	(IN H2O, GAGE)	5.1	6.9	5.9
INTAKE AIR RESTRICTION	(IN H2O, GAGE)	2.0	2.3	2.2
FUEL INLET	(IN Hg, GAGE)	1.1	1.4	1.3
TURBO OIL SUPPLY	(PSIG)	39	45	43
COOLANT THERMOSTAT	(PSIG)	17	18	18

CUMMINS L10-HTT (1600 RPM)
OPERATIONAL SUMMARY

Sponsor Code: A 59	SwRI Code: LO 68186	Start Date: 10/19/93
Engine Number: 001	Test Number: 001	End Date: 10/22/93

		MINIMUM	MAXIMUM	AVERAGE
SPEED	(RPM)	1594	1600	1596
TORQUE	(FT*LB)	1036.7	1080.3	1060.4
POWER	(BHP)	314.7	328.1	321.7
FUEL RATE	(LB/HR)	102.5	109.5	107.3
TEMPERATURES (°F)				
COOLANT OUT		190	192	191
COOLANT IN		176	180	178
OIL GALLERY		280	280	280
INTAKE AIR		81	94	89
OIL SUMP		283	284	283
TURBO OIL SUPPLY		120	198	145
AFTERCOOLER COOLANT INLET		65	80	70
AFTERCOOLER COOLANT OUTLET		107	109	108
FUEL		104	106	105
INTAKE MANIFOLD		114	115	115
COMPRESSOR OUTLET		343	359	352
PUMP OUTLET COOLANT		177	180	179
AMBIENT		81	103	93
EXHAUST FRONT MANIFOLD		1050	1072	1062
EXHAUST REAR MANIFOLD		1045	1077	1068
EXHAUST CYLINDER #1		979	990	984
EXHAUST CYLINDER #2		1012	1031	1024
EXHAUST CYLINDER #3		977	1011	994
EXHAUST CYLINDER #4		1014	1030	1022
EXHAUST CYLINDER #5		1040	1055	1047
EXHAUST CYLINDER #6		1040	1065	1048
EXHAUST AFTER TURBO		777	785	782
PRESSURES				
FUEL RAIL	(PSIG)	160	161	160
OIL FILTER IN	(PSIG)	60	62	61
OIL FILTER OUT	(PSIG)	58	60	58
OIL FILTER DELTA	(PSIG)	2	3	2
OIL GALLERY	(PSIG)	43	43	43
WATER PUMP INLET	(PSIG)	10	10	10
WATER PUMP OUTLET	(PSIG)	28	28	28
COMPRESSOR OUTLET	(IN Hg, ABS)	81.5	84.6	83.2
INTAKE MANIFOLD BOOST	(IN Hg, ABS)	79.5	82.1	80.9
EXHAUST BACK PRESSURE	(IN Hg, GAGE)	0.2	0.3	0.3
EXHAUST MANIFOLD FRONT	(IN Hg, ABS)	69.6	71.7	70.9
EXHAUST MANIFOLD REAR	(IN Hg, ABS)	72.1	74.5	73.5
CRANKCASE	(IN H2O, GAGE)	7.3	8.0	7.7
INTAKE AIR RESTRICTION	(IN H2O, GAGE)	4.3	4.7	4.5
FUEL INLET	(IN Hg, GAGE)	1.8	2.0	1.9
TURBO OIL SUPPLY	(PSIG)	37	45	42
COOLANT THERMOSTAT	(PSIG)	17	18	17


CUMMINS L10-HTT
OIL FILTER DELTA P
Sponsor Code: A 59
SwRI Code: LO 68186
Start Date: 10/19/93
Engine Number: 001
Test Number: 001
End Date: 10/22/93
OIL FILTER DELTA P, PSIG
0
2
4
6
8
10
0
60
120
180
240
TEST HOURS

CUMMINS L10-HTT
TEST FUEL ANALYSIS (Last Batch)

Sponsor Code: OS 108703	SwRI Code: LO 68186	Start Date: 10/19/93
Engine Number: 001	Test Number: 001	End Date: 10/22/93
Batch Identifiers: 93-07	Supplier: Howell	

Measurement	Specs.	Analysis	Test Method
Total Sulfur, wt.%	0.10 - 0.15		D-2622
Gravity, °API	30 - 34		D-287
Hydrocarbon Composition			
Aromatics, vol.%	42 - 47	45.6	D-5186
Olefins, vol.%	Report	2.2	D-1319
Saturates, vol.%	Report	52.2	D-1319
Cetane Index	40	4.02	D-4737
Copper Strip Corrosion	3 Maximum	1	D-130
Flash Point, °C	52 Maximum	73	D-92
Cloud Point, °C	-7 Maximum	-9	D-2500
Carbon Residue on 10% Residium, wt.%	0.20 Maximum	0.12	D-524 (10% Bottoms)
Water and Sediment, vol.%	0.05 Maximum	<0.05	D-2709
Ash, wt.%	0.002 Maximum	0.001	D-482
Kin Viscosity @ 40°C, cSt	1.9 - 4.1	2.7	D-445
Distillation, °C			
IBP		182	D-86
10%		218	D-86
50%	246 - 288	255	D-86
90%	288 - 316	314	D-86
EP	349 Maximum	339	D-86

CUMMINS L10–HTT

UNSCHEDULED DOWNTIME AND MAINTENANCE SUMMARY

Sponsor Code: A 59	SwRI Code: LO 68186	Start Date: 10/19/93
Engine Number: 001	Test Number: 001	End Date: 10/22/93

Number of Downtime Occurrences: 4

Test Hours	Date	Downtime	Reasons
2.5	10–19–93	51 MIN	Oil temperature problem. Flushed oil cooler auxillary heat exchanger.
5.0	10–21–93	40 HR 45 MIN	Oil temperature problem. The oil cooler was replumbed.
20.0	10–22–93	11 HR 10 MIN	As part of the test procedure, engine was shut down for a three hour soak.
21.0	10–22–93		The engine was shutdown due to high crankcase pressure. Number 4 cylinder scuffed due to improper installation of crankcase thrust washers. Test was terminated.
		52 HR 46 MIN	Total downtime.

APPENDIX B

Cummins L10 High-Temperature Cyclic Test
Test No. 002

SOUTHWEST RESEARCH INSTITUTE
San Antonio, Texas

DIVISION OF
AUTOMOTIVE PRODUCTS AND EMISSIONS RESEARCH

Report on

a

CUMMINS L10 HIGH TEMPERATURE TEST

Conducted for

BELVOIR FUELS AND LUBRICANTS RESEARCH FACILITY

A 59

Engine No. 001
Test No. 002

I certify that this evaluation was conducted, to the best of my knowledge, in accordance with the conditions specified in Cummins L10 High Temperature Test Procedure, supplemented by information letters and/or contact with the appropriate test procedure sponsor.

Scott M. Richards
Senior Research Engineer
Department of Gasoline
and Diesel Engine
Lubricants

April 22, 1994

CUMMINS L10-HTT (1200 RPM)
OPERATIONAL SUMMARY

Sponsor Code: A 59	SwRI Code: LO 68186	Start Date: 04/07/94
Engine Number: 001	Test Number: 002	End Date: 04/22/94

	MINIMUM	MAXIMUM	AVERAGE
SPEED (RPM)	1199	1202	1200
TORQUE (FT*LB)	1175.0	1240.5	1204.4
POWER (BHP)	208.1	283.1	273.9
FUEL RATE (LB/HR)	92.8	97.4	95.2
TEMPERATURES (°F)			
COOLANT OUT	274	279	275
COOLANT IN	259	263	260
OIL GALLERY	335	347	342
INTAKE AIR	78	97	94
OIL SUMP	312	342	339
TURBO OIL SUPPLY	116	290	204
AFTERCOOLER COOLANT INLET	55	76	68
AFTERCOOLER COOLANT OUTLET	114	116	115
FUEL	103	112	105
INTAKE MANIFOLD	114	116	115
COMPRESSOR OUTLET	321	347	339
PUMP OUTLET COOLANT	257	260	259
AMBIENT	84	115	97
EXHAUST FRONT MANIFOLD	1288	1356	1329
EXHAUST REAR MANIFOLD	1309	1340	1325
EXHAUST CYLINDER #1	1121	1324	1181
EXHAUST CYLINDER #2	1224	1305	1275
EXHAUST CYLINDER #3	1220	1296	1250
EXHAUST CYLINDER #4	1206	1242	1228
EXHAUST CYLINDER #5	1251	1292	1279
EXHAUST CYLINDER #6	1165	1207	1193
EXHAUST AFTER TURBO	730	1002	968
PRESSURES			
FUEL RAIL (PSIG)	153	157	155
OIL FILTER IN (PSIG)	49	99	57
OIL FILTER OUT (PSIG)	42	64	50
OIL FILTER DELTA (PSIG)	0.3	1.8	0.8
OIL GALLERY (PSIG)	31	45	37
WATER PUMP INLET (PSIG)	10	13	11
WATER PUMP OUTLET (PSIG)	17	23	20
COMPRESSOR OUTLET (IN Hg, ABS)	70.9	86.1	73.2
INTAKE MANIFOLD BOOST (IN Hg, ABS)	69.8	74.5	71.6
EXHAUST BACK PRESSURE (IN Hg, GAGE)	0.1	0.5	0.3
EXHAUST MANIFOLD FRONT (IN Hg, ABS)	54.2	56.5	55.2
EXHAUST MANIFOLD REAR (IN Hg, ABS)	55.7	58.9	56.8
CRANKCASE (IN H2O, GAGE)	5.2	14.1	8.2
INTAKE AIR RESTRICTION (IN H2O, GAGE)	2.0	10.4	2.8
FUEL INLET (IN Hg, GAGE)	1.2	1.8	1.5
TURBO OIL SUPPLY (PSIG)	41	45	43
COOLANT THERMOSTAT (PSIG)	14	23	15

CUMMINS L10–HTT (1600 RPM)
OPERATIONAL SUMMARY

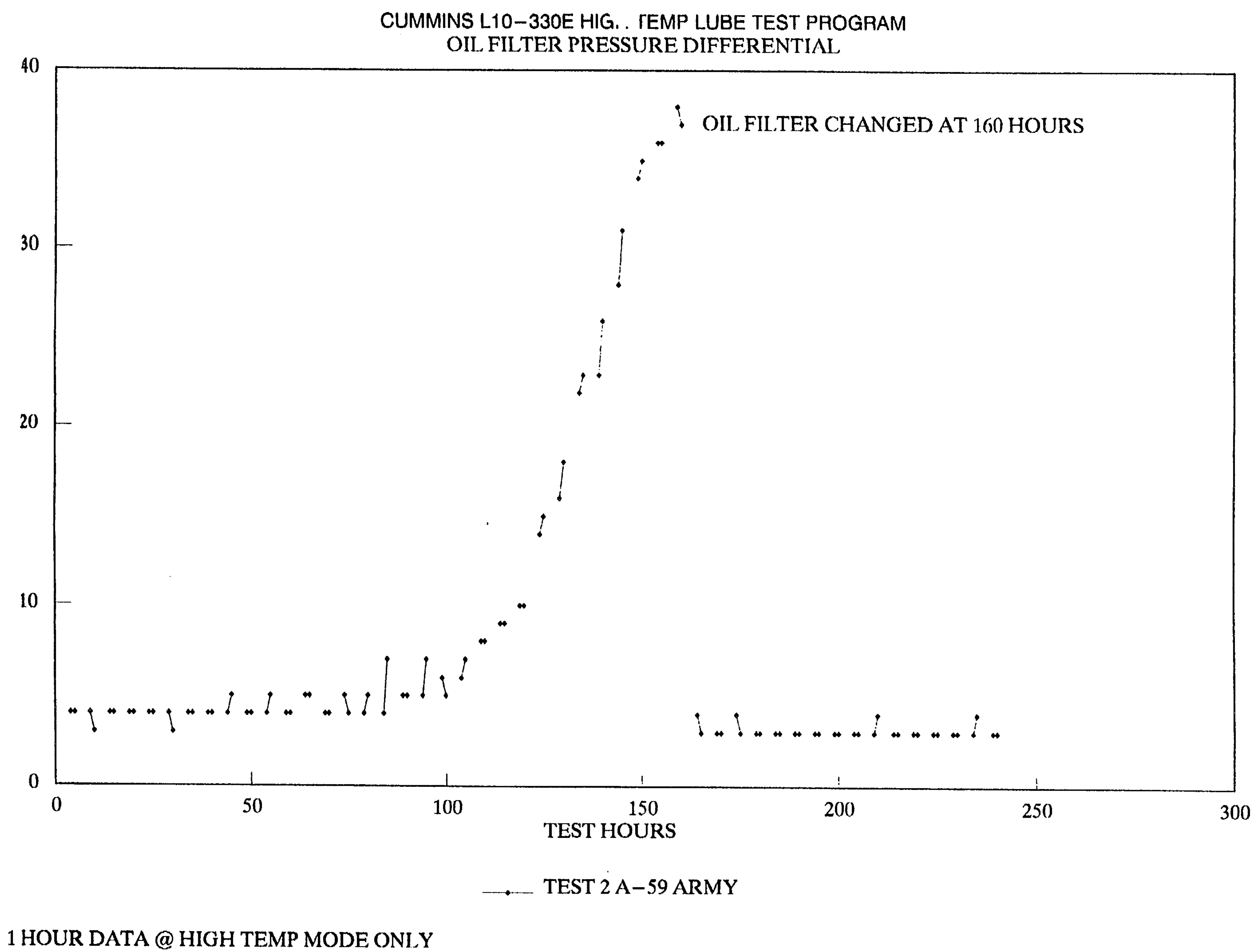
Sponsor Code: A 59	SwRI Code: LO 68186	Start Date: 04/07/94
Engine Number: 001	Test Number: 002	End Date: 04/22/94

		MINIMUM	MAXIMUM	AVERAGE
SPEED	(RPM)	1599	1602	1600
TORQUE	(FT*LB)	1041	1082	1060
POWER	(BHP)	317	329	323
FUEL RATE	(LB/HR)	102.2	109.9	107.1
TEMPERATURES (°F)				
COOLANT OUT		189	191	190
COOLANT IN		176	180	177
OIL GALLERY		271	281	273
INTAKE AIR		87	99	95
OIL SUMP		274	280	275
TURBO OIL SUPPLY		112	259	204
AFTERCOOLER COOLANT INLET		57	78	69
AFTERCOOLER COOLANT OUTLET		105	119	110
FUEL		104	107	105
INTAKE MANIFOLD		114	122	116
COMPRESSOR OUTLET		353	371	364
PUMP OUTLET COOLANT		176	180	178
AMBIENT		77	102	88
EXHAUST FRONT MANIFOLD		1069	1129	1111
EXHAUST REAR MANIFOLD		1085	1114	1099
EXHAUST CYLINDER #1		1005	1447	1097
EXHAUST CYLINDER #2		1025	1096	1063
EXHAUST CYLINDER #3		1010	1095	1056
EXHAUST CYLINDER #4		1011	1052	1024
EXHAUST CYLINDER #5		1026	1072	1048
EXHAUST CYLINDER #6		1033	1087	1062
EXHAUST AFTER TURBO		1033	1087	1062
PRESSURES				
FUEL RAIL	(PSIG)	160	163	160
OIL FILTER IN	(PSIG)	59	100	70
OIL FILTER OUT	(PSIG)	55	66	61
OIL FILTER DELTA	(PSIG)	3	9	4
OIL GALLERY	(PSIG)	40	47	45
WATER PUMP INLET	(PSIG)	7	12	9
WATER PUMP OUTLET	(PSIG)	23	29	26
COMPRESSOR OUTLET	(IN Hg, ABS)	1.9	2.4	2.3
INTAKE MANIFOLD BOOST	(IN Hg, ABS)	78.0	81.3	79.4
EXHAUST BACK PRESSURE	(IN Hg, GAGE)	0.2	0.4	0.3
EXHAUST MANIFOLD FRONT	(IN Hg, ABS)	68.9	71.7	70.9
EXHAUST MANIFOLD REAR	(IN Hg, ABS)	71.6	74.7	72.7
CRANKCASE	(IN H2O, GAGE)	6.8	13.0	10.1
INTAKE AIR RESTRICTION	(IN H2O, GAGE)	1.0	9.9	4.8
FUEL INLET	(IN Hg, GAGE)	1.9	2.4	2.3
TURBO OIL SUPPLY	(PSIG)	40	45	43
COOLANT THERMOSTAT	(PSIG)	14	19	16

CUMMINS L10-HTT
TEST FUEL ANALYSIS (Last Batch)

Sponsor Code: A-59	SwRI Code: LO 68186	Start Date: 04/07/94
Engine Number: 001	Test Number: 002	End Date: 04/22/94
Batch Identifiers: 94-03	Supplier: Howell	

Measurement	Specs.	Analysis	Test Method
Total Sulfur, wt.%	0.10 - 0.15		D-2622
Gravity, °API	30 - 34		D-287
Hydrocarbon Composition			
Aromatics, vol.%	42 - 47		D-5186
Olefins, vol.%	Report		D-1319
Saturates, vol.%	Report		D-1319
Cetane Index	40	40	D-4737
Copper Strip Corrosion	3 Maximum	1	D-130
Flash Point, °C		181	D-92
Cloud Point, °C	20 Maximum	+12	D-2500
Carbon Residue on 10%			D-524
Residium, wt.%			(10% Bottoms)
Water and Sediment, vol.%	0.05 Maximum	<0.05	D-2709
Ash, wt.%	0.002 Maximum	0.002	D-482
Kin Viscosity @ 40°C, cSt			D-445
Distillation, °C			
IBP		382	D-86
10%		409	D-86
50%	475 - 550	481	D-86
90%	550 - 600	587	D-86
EP	660 Maximum	642	D-86


CUMMINS L10-330E HIG.. ΓEMP LUBE TEST PROGRAM
OIL FILTER PRESSURE DIFFERENTIAL
OIL FILTER CHANGED AT 160 HOURS
40
30
20
10
0
0
50
100
150
200
250
300
TEST HOURS
TEST 2 A-59 ARMY
1 HOUR DATA @ HIGH TEMP MODE ONLY

CUMMINS L10-HTT

OIL CONSUMPTION SUMMARY

Sponsor Code: A 59	SwRI Code: LO 68186	Start Date: 04/07/94
Engine Number: 001	Test Number: 002	End Date: 04/22/94

TEST HOURS	RATE, LB/HR
20	0.093
40	0.182
60	0.347
80	0.316
100	0.135
120	0.179
140	0.150
160	0.353
180	0.161
200	0.183
220	0.188
240	0.155
Test Avg	0.204

CUMMINS L10-HTT
HEAVY CROWNLAND CARBON

Sponsor Code: A 59	SwRI Code: LO 68186	Start Date: 04/07/94
Engine Number: 001	Test Number: 002	End Date: 04/22/94

Piston No.	Carbon Remaining	Carbon Lost	Total Carbon
1	2	0	2
2	2	0	2
3	1	1	2
4	3	1	4
5	1	0	1
6	1	0	1
		Average	2

1.0 TEST IDENTIFICATION

FTMS 791, Method	Laboratory	Oil Code
341 L-10	SwRI	

Stand No.	Stand Run No.	Engine No.	Fuel (Mfr.-Batch)
1	01	82-(#1)	Howell Hydrocarbons

Date Started	Date Completed	Test Hours
/ /	05/13/94	1

2.0 REFERENCE TESTS

STAND LAST REFERENCE	Engine No.	Date Completed	Oil I.D.
Stand No. Stand Run No.	Test Rating WTD= ,TGF= .0%		Industry Average WTD= ,TGF= %

LAB LAST REFERENCE	Engine No.	Date Completed	Oil I.D.
Stand No. Stand Run No.	Test Rating WTD= ,TGF= .0%		Industry Average WTD= ,TGF= %

3.0 EVALUATION OF ENGINE PARTS

3.1 Piston Deposits (Groove Backs and Lands)

Dep. Type		Dep. Fct.	Grooves No. 1 A,%	Grooves No. 1 Dem.	Grooves No. 2 A,%	Grooves No. 2 Dem.	Grooves No. 3 A,%	Grooves No. 3 Dem.	Grooves No. 4 A,%	Grooves No. 4 Dem.	Lands No. 2 A,%	Lands No. 2 Dem.	Lands No. 3 A,%	Lands No. 3 Dem.	Lands No. 4 A,%	Lands No. 4 Dem.
CARBON	HC	1.000	35	35.00	65	65.00										
	MHC	0.750														
	MC	0.500	65	32.50	25	12.50										
	LC	0.250			10	2.50					85	21.25	80	20.00		
	VLC	0.150														
	Total		100	67.50	100	80.00					85	21.25	80	20.00		
LACQUER	BL	0.100					95	9.500			10	1.000	15	1.500		
	DBRL	0.075					5	0.375					5	0.375	100	7.500
	AL	0.050														
	LAL	0.025									5	0.125				
	VLAL	0.010														
	RL	0.000														
	Total						100	9.875			15	1.125	20	1.875	100	7.500
Clean									100							
Rating				67.500		80.000		9.875		0.000		22.375		21.875		7.500
Location Factor				1		10		35		70		3.5		20		35
Weighted Rating				67.500		800.000		345.625		0.000		78.313		437.500		262.500

Total Weighted Demerit	1991.
Top Groove Filling, %	60

RATER: DS

MULTI-CYLINDER ENGINE TESTS L-10

TEST NO. 1-01 OIL CODE ______ DATE 05/13/94

3.2 SUPPLEMENTAL PISTON DEPOSITS (GROOVE SIDES & RINGS)

DEPOSIT TYPE			CARBON			LACQUER					
			HC	MC	LC	BL	DBRL	AL	LAL	VLAL	RL
SKIRT											
UN-CROWN					100						
LINER ABOVE RING TRAVEL											
PISTON CROWN			2		98						
GROOVE TOP AND BOTTOM	1	T									
		B									
	2	T									
		B									
	3	T									
		B									
	4	T									
		B									
TOP & BOTTOM BACK OF RINGS	1	T									
		B									
		BK									
	2	T									
		B									
		BK									
	3	T									
		B									
		BK									
	4	T									
		B									
		BK									

3.3 ADDITIONAL DEPOSIT & CONDITION RATINGS

A. Piston Crown Scuffing (Nature and Quantity) Nil

B. Amount and Nature of Deposits on Oil Ring Slots Nil

C. Piston Skirt Condition (Not Including Deposits) Polished areas normal few fine to coarse vertical lines

D. Liner Condition Normal

1.0 TEST IDENTIFICATION

FTMS 791, Method 341 L-10	Laboratory SwRI		Oil Code	
Stand No. 1	Stand Run No. 02	Engine No. 82-(#2)	Fuel (Mfr.-Batch) Howell Hydrocarbons	
Date Started / /		Date Completed 05/13/94		Test Hours 1

2.0 REFERENCE TESTS

STAND LAST REFERENCE Stand No. Stand Run No.	Engine No.	Date Completed		Oil I.D.
	Test Rating WTD= ,TGF= .0%		Industry Average WTD= ,TGF= %	
LAB LAST REFERENCE Stand No. Stand Run No.	Engine No.	Date Completed		Oil I.D.
	Test Rating WTD= ,TGF= .0%		Industry Average WTD= ,TGF= %	

3.0 EVALUATION OF ENGINE PARTS

3.1 Piston Deposits (Groove Backs and Lands)

	Dep. Type	Dep. Fct.	Grooves								Lands					
			No. 1		No. 2		No. 3		No. 4		No. 2		No. 3		No. 4	
			A,%	Dem.	A,%	Dem.	A,%	Dem.	A,%	Dem.	A,%	Dem.	A,%	Dem.	A,%	Dem.
CARBON	HC	1.000	15	15.00	35	35.00					10	10.00				
	MHC	0.750														
	MC	0.500	85	42.50	45	22.50										
	LC	0.250			20	5.00					65	16.25	75	18.75		
	VLC	0.150														
	Total		100	57.50	100	62.50					75	26.25	75	18.75		
LACQUER	BL	0.100					70	7.000					10	1.000		
	DBRL	0.075					10	0.750					10	0.750	80	6.000
	AL	0.050					20	1.000			5	0.250	5	0.250	20	1.000
	LAL	0.025									20	0.500				
	VLAL	0.010														
	RL	0.000														
	Total						100	8.750			25	0.750	25	2.000	100	7.000
Clean									100							
Rating				57.500		62.500		8.750		0.000		27.000		20.750		7.000
Location Factor				1		10		35		70		3.5		20		35
Weighted Rating				57.500		625.000		306.250		0.000		94.500		415.000		245.000

Total Weighted Demerit	1743.
Top Groove Filling, %	55

RATER: DS

MULTI-CYLINDER ENGINE TESTS L-10

TEST NO. 1-02 OIL CODE DATE 05/13/94

3.2 SUPPLEMENTAL PISTON DEPOSITS (GROOVE SIDES & RINGS)

DEPOSIT TYPE			CARBON			LACQUER						
			HC	MC	LC	BL	DBRL	AL	LAL	VLAL	RL
SKIRT												
UN-CROWN					100							
LINER ABOVE RING TRAVEL												
PISTON CROWN			2		98							
GROOVE TOP AND BOTTOM	1	T										
		B										
	2	T										
		B										
	3	T										
		B										
	4	T										
		B										
TOP & BOTTOM BACKS OF RINGS	1	T										
		B										
		BK										
	2	T										
		B										
		BK										
	3	T										
		B										
		BK										
	4	T										
		B										
		BK										

3.3 ADDITIONAL DEPOSIT & CONDITION RATINGS

A. Piston Crown Scuffing (Nature and Quantity) Nil

B. Amount and Nature of Deposits on Oil Ring Slots Nil

C. Piston Skirt Condition (Not Including Deposits) Polished areas normal few fine to coarse vertical lines

D. Liner Condition Normal

1.0 TEST IDENTIFICATION

FTMS 791, Method	Laboratory	Oil Code
341 L-10	SwRI	

Stand No.	Stand Run No.	Engine No.	Fuel (Mfr.-Batch)
1	03	82-(#3)	Howell Hydrocarbons

Date Started	Date Completed	Test Hours
/ /	05/13/94	1

2.0 REFERENCE TESTS

STAND LAST REFERENCE	Engine No.	Date Completed	Oil I.D.
Stand No. Stand Run No.	Test Rating WTD= ,TGF= .0%		Industry Average WTD= ,TGF= %

LAB LAST REFERENCE	Engine No.	Date Completed	Oil I.D.
Stand No. Stand Run No.	Test Rating WTD= ,TGF= .0%		Industry Average WTD= ,TGF= %

3.0 EVALUATION OF ENGINE PARTS

3.1 Piston Deposits (Groove Backs and Lands)

	Dep.	Dep.	Grooves								Lands					
			No. 1		No. 2		No. 3		No. 4		No. 2		No. 3		No. 4	
	Type	Fct.	A,%	Dem.	A,%	Dem.	A,%	Dem.	A,%	Dem.	A,%	Dem.	A,%	Dem.	A,%	Dem.
CARBON	HC	1.000	50	50.00	10	10.00					10	10.00				
	MHC	0.750														
	MC	0.500	40	20.00	50	25.00										
	LC	0.250	10	2.50	35	8.75	25	6.25			85	21.25	95	23.75		
	VLC	0.150														
	Total		100	72.50	95	43.75	25	6.25			95	31.25	95	23.75		
LACQUER	BL	0.100					75	7.500								
	DBRL	0.075											5	0.375	100	7.500
	AL	0.050			5	0.250					5	0.250				
	LAL	0.025														
	VLAL	0.010														
	RL	0.000														
	Total				5	0.250	75	7.500			5	0.250	5	0.375	100	7.500
Clean									100							
Rating				72.500		44.000		13.750		0.000		31.500		24.125		7.500
Location Factor				1		10		35		70		3.5		20		35
Weighted Rating				72.500		440.000		481.250		0.000		110.250		482.500		262.500

Total Weighted Demerit	1849.
Top Groove Filling, %	70

RATER: DS

MULTI-CYLINDER ENGINE TESTS L-10

TEST NO. 1-03 OIL CODE ______ DATE 05/13/94

3.2 SUPPLEMENTAL PISTON DEPOSITS (GROOVE SIDES & RINGS)

DEPOSIT TYPE			CARBON			LACQUER					
			HC	MC	LC	BL	DBRL	AL	LAL	VLAL	RL
SKIRT											
UN-CROWN					100						
LINER ABOVE RING TRAVEL											
PISTON CROWN			1		99						
GROOVE TOP AND BOTTOM	1	T									
		B									
	2	T									
		B									
	3	T									
		B									
	4	T									
		B									
TOP BOTTOM & BACK OF RINGS	1	T									
		B									
		BK									
	2	T									
		B									
		BK									
	3	T									
		B									
		BK									
	4	T									
		B									
		BK									

3.3 ADDITIONAL DEPOSIT & CONDITION RATINGS

A. Piston Crown Scuffing (Nature and Quantity) Nil

B. Amount and Nature of Deposits on Oil Ring Slots Nil

C. Piston Skirt Condition (Not Including Deposits) Polished areas normal few fine to coarse vertical lines

D. Liner Condition Normal

1.0 TEST IDENTIFICATION

FTMS 791, Method 341 L-10	Laboratory SwRI	Oil Code	
Stand No. 1	Stand Run No. 04	Engine No. 82-(#4)	Fuel (Mfr.-Batch) Howell Hydrocarbons
Date Started / /	Date Completed 05/13/94	Test Hours 1	

2.0 REFERENCE TESTS

STAND LAST REFERENCE Stand No. Stand Run No.	Engine No.	Date Completed	Oil I.D.
	Test Rating WTD= ,TGF= .0%		Industry Average WTD= ,TGF= %
LAB LAST REFERENCE Stand No. Stand Run No.	Engine No.	Date Completed	Oil I.D.
	Test Rating WTD= ,TGF= .0%		Industry Average WTD= ,TGF= %

3.0 EVALUATION OF ENGINE PARTS

3.1 Piston Deposits (Groove Backs and Lands)

	Dep. Type	Dep. Fct.	Grooves No. 1 A,%	Grooves No. 1 Dem.	Grooves No. 2 A,%	Grooves No. 2 Dem.	Grooves No. 3 A,%	Grooves No. 3 Dem.	Grooves No. 4 A,%	Grooves No. 4 Dem.	Lands No. 2 A,%	Lands No. 2 Dem.	Lands No. 3 A,%	Lands No. 3 Dem.	Lands No. 4 A,%	Lands No. 4 Dem.
CARBON	HC	1.000	5	5.00	9	9.00					15	15.00				
	MHC	0.750														
	MC	0.500	5	2.50												
	LC	0.250	90	22.50	10	2.50					60	15.00	75	18.75		
	VLC	0.150														
	Total		100	30.00	19	11.50					75	30.00	75	18.75		
LACQUER	BL	0.100					100	10.000					10	1.000		
	DBRL	0.075											10	0.750	100	7.500
	AL	0.050									5	0.250	5	0.250		
	LAL	0.025														
	VLAL	0.010									20	0.200				
	RL	0.000														
	Total						100	10.000			25	0.450	25	2.000	100	7.500
Clean					81				100							
Rating				30.000		11.500		10.000		0.000		30.450		20.750		7.500
Location Factor				1		10		35		70		3.5		20		35
Weighted Rating				30.000		115.000		350.000		0.000		106.575		415.000		262.500

Total Weighted Demerit	1279.
Top Groove Filling, %	25

RATER: DS

MULTI-CYLINDER ENGINE TESTS L-10

TEST NO. 1-04 OIL CODE ______ DATE 05/13/94

3.2 SUPPLEMENTAL PISTON DEPOSITS (GROOVE SIDES & RINGS)

DEPOSIT TYPE			CARBON			LACQUER					
			HC	MC	LC	BL	DBRL	AL	LAL	VLAL	RL
SKIRT											
UN-CROWN					100						
LINER ABOVE RING TRAVEL											
PISTON CROWN			3		97						
GROOVE TOP AND BOTTOM	1	T									
		B									
	2	T									
		B									
	3	T									
		B									
	4	T									
		B									
TOP BOTTOM & BACK OF RINGS	1	T									
		B									
		BK									
	2	T									
		B									
		BK									
	3	T									
		B									
		BK									
	4	T									
		B									
		BK									

3.3 ADDITIONAL DEPOSIT & CONDITION RATINGS

A. Piston Crown Scuffing (Nature and Quantity) Nil

B. Amount and Nature of Deposits on Oil Ring Slots Nil

C. Piston Skirt Condition (Not Including Deposits) Polished areas normal few fine to coarse vertical lines

D. Liner Condition Normal

1.0 TEST IDENTIFICATION

FTMS 791, Method 341 L-10	Laboratory SwRI	Oil Code	
Stand No. 1	Stand Run No. 05	Engine No. 82-(#5)	Fuel (Mfr.-Batch) Howell Hydrocarbons
Date Started / /	Date Completed 05/13/94	Test Hours 1	

2.0 REFERENCE TESTS

STAND LAST REFERENCE Stand No. Stand Run No.	Engine No.	Date Completed	Oil I.D.
	Test Rating WTD= ,TGF= .0%		Industry Average WTD= ,TGF= %
LAB LAST REFERENCE Stand No. Stand Run No.	Engine No.	Date Completed	Oil I.D.
	Test Rating WTD= ,TGF= .0%		Industry Average WTD= ,TGF= %

3.0 EVALUATION OF ENGINE PARTS

3.1 Piston Deposits (Groove Backs and Lands)

	Dep.	Dep.	Grooves								Lands					
			No. 1		No. 2		No. 3		No. 4		No. 2		No. 3		No. 4	
	Type	Fct.	A,%	Dem.	A,%	Dem.	A,%	Dem.	A,%	Dem.	A,%	Dem.	A,%	Dem.	A,%	Dem.
CARBON	HC	1.000	10	10.00	75	75.00										
	MHC	0.750														
	MC	0.500	90	45.00	25	12.50										
	LC	0.250									80	20.00	80	20.00		
	VLC	0.150														
	Total		100	55.00	100	87.50					80	20.00	80	20.00		
LACQUER	BL	0.100					85	8.500			5	0.500	15	1.500		
	DBRL	0.075					15	1.125			5	0.375	5	0.375	100	7.500
	AL	0.050									5	0.250				
	LAL	0.025									5	0.125				
	VLAL	0.010														
	RL	0.000														
	Total						100	9.625			20	1.250	20	1.875	100	7.500
Clean									100							
Rating				55.000		87.500		9.625		0.000		21.250		21.875		7.500
Location Factor				1		10		35		70		3.5		20		35
Weighted Rating				55.000		875.000		336.875		0.000		74.375		437.500		262.500

Total Weighted Demerit	2041.
Top Groove Filling, %	55

RATER: DS

MULTI-CYLINDER ENGINE TESTS L-10

TEST NO. 1-05 OIL CODE ______________ DATE 05/13/94

3.2 SUPPLEMENTAL PISTON DEPOSITS (GROOVE SIDES & RINGS)

DEPOSIT TYPE			CARBON			LACQUER					
			HC	MC	LC	BL	DBRL	AL	LAL	VLAL	RL
SKIRT											
UN-CROWN					100						
LINER ABOVE RING TRAVEL											
PISTON CROWN			1		99						
GROOVE TOP AND BOTTOM	1	T									
		B									
	2	T									
		B									
	3	T									
		B									
	4	T									
		B									
TOP BOTTOM & BACK OF RINGS	1	T									
		B									
		BK									
	2	T									
		B									
		BK									
	3	T									
		B									
		BK									
	4	T									
		B									
		BK									

3.3 ADDITIONAL DEPOSIT & CONDITION RATINGS

A. Piston Crown Scuffing (Nature and Quantity) Nil

B. Amount and Nature of Deposits on Oil Ring Slots Nil

C. Piston Skirt Condition (Not Including Deposits) Polished areas normal few fine to coarse vertical lines

D. Liner Condition Normal

1.0 TEST IDENTIFICATION

FTMS 791, Method	Laboratory	Oil Code
341 L-10	SwRI	

Stand No.	Stand Run No.	Engine No.	Fuel (Mfr.-Batch)
1	06	82-(#6)	Howell Hydrocarbons

Date Started	Date Completed	Test Hours
/ /	05/13/94	1

2.0 REFERENCE TESTS

STAND LAST REFERENCE	Engine No.	Date Completed	Oil I.D.
Stand No. Stand Run No.	Test Rating WTD= ,TGF= .0%		Industry Average WTD= ,TGF= %

LAB LAST REFERENCE	Engine No.	Date Completed	Oil I.D.
Stand No. Stand Run No.	Test Rating WTD= ,TGF= .0%		Industry Average WTD= ,TGF= %

3.0 EVALUATION OF ENGINE PARTS

3.1 Piston Deposits (Groove Backs and Lands)

	Dep.	Dep.	Grooves								Lands					
			No. 1		No. 2		No. 3		No. 4		No. 2		No. 3		No. 4	
	Type	Fct.	A,%	Dem.	A,%	Dem.	A,%	Dem.	A,%	Dem.	A,%	Dem.	A,%	Dem.	A,%	Dem.
CARBON	HC	1.000	20	20.00	25	25.00										
	MHC	0.750														
	MC	0.500	80	40.00	55	27.50										
	LC	0.250			20	5.00					70	17.50	95	23.75		
	VLC	0.150														
	Total		100	60.00	100	57.50					70	17.50	95	23.75		
LACQUER	BL	0.100					90	9.000			5	0.500				
	DBRL	0.075					10	0.750			5	0.375			100	7.500
	AL	0.050									5	0.250	5	0.250		
	LAL	0.025									15	0.375				
	VLAL	0.010														
	RL	0.000														
	Total						100	9.750			30	1.500	5	0.250	100	7.500
Clean									100							
Rating				60.000		57.500		9.750		0.000		19.000		24.000		7.500
Location Factor				1		10		35		70		3.5		20		35
Weighted Rating				60.000		575.000		341.250		0.000		66.500		480.000		262.500

Total Weighted Demerit	1785.
Top Groove Filling, %	50

RATER: DS

MULTI-CYLINDER ENGINE TESTS L-10

TEST NO. 1-06 OIL CODE ______ DATE 05/13/94

3.2 SUPPLEMENTAL PISTON DEPOSITS (GROOVE SIDES & RINGS)

DEPOSIT TYPE			CARBON			LACQUER					
			HC	MC	LC	BL	DBRL	AL	LAL	VLAL	RL
SKIRT											
UN-CROWN					100						
LINER ABOVE RING TRAVEL											
PISTON CROWN			1		99						
GROOVE TOP AND BOTTOM	1	T									
		B									
	2	T									
		B									
	3	T									
		B									
	4	T									
		B									
TOP BOTTOM & BACK OF RINGS	1	T									
		B									
		BK									
	2	T									
		B									
		BK									
	3	T									
		B									
		BK									
	4	T									
		B									
		BK									

3.3 ADDITIONAL DEPOSIT & CONDITION RATINGS

A. Piston Crown Scuffing (Nature and Quantity) Nil

B. Amount and Nature of Deposits on Oil Ring Slots Nil

C. Piston Skirt Condition (Not Including Deposits) Polished areas normal few fine to coarse vertical lines

D. Liner Condition Normal

CUMMINS L10-HTT

CYLINDER LINER RATING

Sponsor Code: A 59	SwRI Code: LO 68186	Start Date: 04/07/94
Engine Number: 001	Test Number: 002	End Date: 04/22/94

Cylinder Number	Ring Travel Area				Above Top Ring Travel	
	% Heavy Polish		% Crosshatch		% Heavy Polish	
	T	A-T	T	A-T	T	A-T
1	5	5	96	94	0	0
2	2	2	92	93	0	0
3	17	20	70	60	2	2
4	2	4	92	90	0	0
5	5	8	90	88	0	0
6	3	2	92	91	0	0
Averages	5.66	6.83	88.66	86.00	0.33	0.33
Average T and A-T		6.25		87.33		0.33

CUMMINS L10-HTT

PISTON SKIRT RATING

Sponsor Code: A 59	SwRI Code: LO 68186	Start Date: 04/07/94
Engine Number: 001	Test Number: 002	End Date: 04/22/94

Cylinder Number	Thrust	Anti-Thrust
1	Light Scratches	Light Scratches
2	Light Scratches	Light Scratches
3	Very Light Scratches	Very Light Scratches
4	Light Scratches	Light Scratches
5	Light Scratches	Light Scratches
6	Light Scratches	Light Scratches

CUMMINS L10-HTT
PISTON RING ASSESSMENTS

Sponsor Code: A 59	SwRI Code: LO 68186	Start Date: 04/07/94
Engine Number: 001	Test Number: 002	End Date: 04/22/94

Ring Face Conditions

Cylinder Number	Ring No. 1	Ring No. 2
1	0% Discolored	0% Discolored
2	0% Discolored	0% Discolored
3	0% Discolored	25% Discolored
4	0% Discolored	0% Discolored
5	60% Discolored	0% Discolored
6	0% Discolored	0% Discolored

Ring Freedom

Cylinder Number	Ring No. 1	Ring No. 2	Ring No. 3
1	F	F	F
2	F	F	F
3	F	F	F
4	Hot Stuck 90	F	F
5	F	F	F
6	F	F	F

CUMMINS L10–HTT

UNSCHEDULED DOWNTIME AND MAINTENANCE SUMMARY

Sponsor Code: A–59	SwRI Code: LO 68186	Start Date: 04/07/94
Engine Number: 001	Test Number: 002	End Date: 04/22/94

Number of Downtime Occurrences: 14

Test Hours	Date	Downtime	Reasons
75	04/07/94	1 Hr. 50 Mins.	Replaced exhaust elbow which was cracked: Restart.
27	04/08/94	16 Hrs. 50 Mins.	Tightened fitting @ water pump: Restart.
42.50	04/10/94	23 Hrs. 50 Mins.	Coolant leak @ steel braided line connecting to water pump
			On hold as per engineer: Restart.
43.25	04/11/94	1 Hr. 50 Mins.	Replaced overflow hose: Restart.
43.50	04/11/94	2 Hrs. 75 Mins.	Replaced coolant out thermocouple: Restart.
54.50	04/12/94	6 Hrs. 25 Mins.	Replaced turbo drain line and gasket: Restart.
70.00	04/13/94	7 Hrs. 50 Mins.	Remove, inspect, reseal auxilllary pump seal: Restart.
73.00	04/13/94	1 Hr.	Replaced gasket on auxillary oil pump: Restart.
80.00	04/14/94	11 Hrs. 50 Mins.	Soak. Hold as per instructions: Restart.
100.00	04/15/94	13 Hrs. 75 Mins.	Repair and replaced pump seal: Restart.
160.00	04/18/94	4 Hrs.	Soak and replaced oil filter: Restart.
180.00	04/19/94	4 Hrs.	Soak: Restart.
221.75	04/21/94	1 Hr.	Cleaned screen on regulator: Restart.
234.75	04/22/94	6 Hrs.	Replaced hose on oil cooler: Restart.
		63 Hrs. 54 Mins.	Total Downtime

APPENDIX C

Cummins L10 High-Temperature Cyclic Test Engine Hardware Review and Measurements

Engine Hardware Review

Engine Model: 91L-10 330E

Engine Serial Number: 34654546

Test Description: Transient operating condition, 240-hour high-temperature lubricant test

Oil Identification: A-59, 240 hours

Date: 31 August 1994

Camshaft: No abnormal wear. Reinstalled in engine.

Camshaft Bushings: No evidence of corrosion, pitting, or wear. Not removed from engine.

Camshaft Follower Assembly: Ball sockets do not show any wear. Rollers have some play on their axles, some fine circumferential scratches. One roller revealed some pitting.

Connecting Rod Pin Bushing: Severe discoloration, possible deposition, and pitting (fatigue). Pitting is at the twelve o'clock position. Worn through overlay and copper exposed at the six o'clock position. Average 75 percent exposed copper at the six o'clock position of the bushing.

Connecting Rod Bearings: Some circumferential scratches, otherwise normal wear. Overlay still intact.

Crankshaft: No abnormal wear. Reinstalled in engine.

Thrust Bearings: No abnormal wear.

Main Bearings: Uppers show nothing more than normal wear. However, there are signs of corrosion through to the copper around the oil hole. Lowers show discoloration, small amount of pitting, and less than 1-percent exposed copper.

Liners: Crosshatch still shows with light polish; no evidence of scuffing. Heavy polish evident at top of ring travel on Cylinder Nos. 3 and 5. Cylinder No. 3 has approximately 20-percent bore polish. Outside diameter of liners looks good; no evidence of sludge.

Liner Seals: Look good.

Pistons: Reference Piston Rating information for more detail.
- **Crown:**
- **Lands:**
- **Grooves:**
- **Skirts:** Very-light to light scratches.
- **Pin Bores:** Severely pitted and discolored.

Pistons, Cont'd

Pins: Slightly discolored. No evidence of wear.

Undercrowns: Light-to-medium flaky carbon deposit.

Piston Rings:

Top: No apparent ring face distress.

Middle: No apparent ring face distress.

Bottom: No apparent ring face distress.

Push Tubes:

Valve push tubes show no evidence of wear. Several injector push rods reveal wear on socket at lever end. Follower ends look good.

Rocker Lever Assembly:

Shaft: Worn on loaded side, with a wear scar evident to the touch.

Ball and Sockets: Valve levers look good. Several injector levers show abnormal wear.

Injector Levers: Bushing shows severe wear with some pitting.

Valve Levers: Polished bushing shows some discoloration. Oil deposits are evident around the oil feed hole.

Crossheads: Normal wear, slightly polished.

Injectors: Two show abnormal wear on injector link ball. Remaining four appear normal.

Valve Seals: Appear normal.

Valves: Two replaced due to excessive recession. Normal to slightly above normal beat-in.

Valve Collets: Look good. Reinstalled in engine.

Cummins L10-330E Engine
Piston Ring End Gaps

cyl #	ring position	Before	After	Change
	Top Ring	0.029	0.034	0.005
1	Intermediate Ring	0.045	0.050	0.005
	Oil Ring	0.032	0.027	-0.005
	Top Ring	0.030	0.034	0.004
2	Intermediate Ring	0.047	0.049	0.002
	Oil Ring	0.032	0.035	0.003
	Top Ring	0.032	0.032	0.000
3	Intermediate Ring	0.053	0.051	-0.002
	Oil Ring	0.028	0.031	0.003
	Top Ring	0.031	0.034	0.003
4	Intermediate Ring	0.046	0.048	0.002
	Oil Ring	0.033	0.035	0.002
	Top Ring	0.031	0.033	0.002
5	Intermediate Ring	0.047	0.046	-0.001
	Oil Ring	0.032	0.035	0.003
	Top Ring	0.031	0.034	0.003
6	Intermediate Ring	0.047	0.046	-0.001
	Oil Ring	0.032	0.036	0.004

Average Change

Top Ring	0.003
Intermediate Ring	0.001
Oil Ring	0.002

Cummins L10-330E Engine
Piston Pin to Articulated Crown

	Before						After						Change	
cyl #	pin	pin bore	clearence	pin	pin bore	clearence	pin	pin bore	clearence	pin	pin bore	clearence	Δ	
1	2.1260	2.1277	0.0017	2.1260	2.1276	0.0016	2.1259	2.1287	0.0028	2.1259	2.1287	0.0028	0.0011	0.0012
	2.1260	2.1279	0.0019	2.1260	2.1279	0.0019	2.1259	2.1275	0.0016	2.1259	2.1275	0.0016	-0.0003	-0.0003
2	2.1261	2.1279	0.0018	2.1260	2.1277	0.0017	2.1259	2.1295	0.0036	2.1259	2.1295	0.0036	0.0018	0.0019
	2.1259	2.1277	0.0018	2.1260	2.1278	0.0018	2.1259	2.1274	0.0015	2.1259	2.1274	0.0015	-0.0003	-0.0003
3	2.1260	2.1277	0.0017	2.1260	2.1277	0.0017	2.1259	2.1266	0.0007	2.1259	2.1266	0.0007	-0.0010	-0.0010
	2.1260	2.1280	0.0020	2.1260	2.1277	0.0017	2.1259	2.1268	0.0009	2.1259	2.1268	0.0009	-0.0011	-0.0008
4	2.1259	2.1279	0.0020	2.1260	2.1277	0.0017	2.1259	2.1296	0.0037	2.1259	2.1296	0.0037	0.0017	0.0020
	2.1260	2.1280	0.0020	2.1259	2.1278	0.0019	2.1258	2.1274	0.0016	2.1258	2.1274	0.0016	-0.0004	-0.0003
5	2.1259	2.1279	0.0020	2.1260	2.1278	0.0018	2.1258	2.1300	0.0042	2.1258	2.1300	0.0042	0.0022	0.0024
	2.1260	2.1280	0.0020	2.1259	2.1277	0.0018	2.1259	2.1274	0.0016	2.1258	2.1274	0.0016	-0.0004	-0.0002
6	2.1259	2.1279	0.0020	2.1259	2.1280	0.0021	2.1259	2.1295	0.0036	2.1259	2.1295	0.0036	0.0016	0.0015
	2.1259	2.1280	0.0021	2.1260	2.1278	0.0018	2.1258	2.1276	0.0018	2.1258	2.1276	0.0018	-0.0003	0.0000

Piston Pin O.D.	inches
Min	2.1259
Max	2.1261
Crown Pin Bore I.D.	
Min	2.1277
Max	2.1281
Clearence	
Min	0.0016
Max	0.0022

Pin and pin bore measurements taken at locations corresponding to the piston crown pin boss, and at two perpendicular locations.

Average Change	
vertical	0.0013
horizontal	-0.0004

Cummins L10-330E Engine
Piston Pin to Articulated Skirt

	Before						After						Change	
cyl #	pin	pin bore	clearence	pin	pin bore	clearence	pin	pin bore	clearence	pin	pin bore	clearence	Δ	
1	2.1260	2.1265	0.0005	2.1260	2.1264	0.0004	2.1259	2.1266	0.0007	2.1259	2.1266	0.0007	0.0002	0.0003
	2.1260	2.1264	0.0004	2.1260	2.1264	0.0004	2.1259	2.1266	0.0007	2.1259	2.1266	0.0007	0.0003	0.0003
2	2.1261	2.1266	0.0005	2.1260	2.1265	0.0005	2.1259	2.1268	0.0009	2.1259	2.1268	0.0009	0.0004	0.0004
	2.1259	2.1264	0.0005	2.1260	2.1265	0.0005	2.1259	2.1267	0.0008	2.1259	2.1267	0.0008	0.0003	0.0003
3	2.1260	2.1265	0.0005	2.1260	2.1265	0.0005	2.1259	2.1264	0.0005	2.1259	2.1264	0.0005	-0.0000	-0.0000
	2.1260	2.1263	0.0003	2.1260	2.1266	0.0006	2.1259	2.1262	0.0003	2.1259	2.1262	0.0003	-0.0000	-0.0003
4	2.1259	2.1266	0.0007	2.1260	2.1265	0.0005	2.1259	2.1269	0.0010	2.1259	2.1269	0.0010	0.0003	0.0005
	2.1260	2.1266	0.0006	2.1259	2.1266	0.0007	2.1258	2.1266	0.0008	2.1258	2.1266	0.0008	0.0002	0.0001
5	2.1259	2.1266	0.0007	2.1260	2.1264	0.0004	2.1258	2.1265	0.0007	2.1258	2.1265	0.0007	0.0000	0.0003
	2.1260	2.1264	0.0004	2.1259	2.1265	0.0006	2.1259	2.1263	0.0005	2.1258	2.1263	0.0005	0.0001	-0.0001
6	2.1259	2.1264	0.0005	2.1259	2.1263	0.0004	2.1259	2.1270	0.0011	2.1259	2.1270	0.0011	0.0006	0.0007
	2.1259	2.1263	0.0004	2.1260	2.1264	0.0004	2.1258	2.1267	0.0009	2.1258	2.1267	0.0009	0.0005	0.0005

Piston Pin O.D.		inches
	Min	2.1259
	Max	2.1261
Skirt Pin Bore I.D.		
	Min	2.1263
	Max	2.1266
Clearence		
	Min	0.0002
	Max	0.0007

Pin and pin bore measurements taken at locations corresponding to the piston skirt pin boss, and at two perpendicular locations.

Average Change	
vertical	0.0003
horizontal	0.0002

Cummins L10-330E Engine
Piston Pin to Rod Bushing

	Before			After			Change
cyl #	pin	bushing	clearence	pin	pin bore	clearence	Δ
1	2.1260	2.1285	0.0025	2.1259	2.1280	0.0021	-0.0004
	2.1260	2.1286	0.0026	2.1259	2.1282	0.0023	-0.0003
2	2.1261	2.1285	0.0024	2.1259	2.1279	0.0020	-0.0004
	2.1259	2.1283	0.0024	2.1259	2.1279	0.0020	-0.0004
3	2.1260	2.1281	0.0021	2.1259	2.1280	0.0021	0.0000
	2.1260	2.1281	0.0021	2.1259	2.1281	0.0022	0.0001
4	2.1259	2.1284	0.0025	2.1259	2.1283	0.0024	-0.0001
	2.1260	2.1283	0.0023	2.1258	2.1281	0.0023	0.0000
5	2.1259	2.1284	0.0025	2.1259	2.1282	0.0023	-0.0002
	2.1260	2.1283	0.0023	2.1259	2.1282	0.0023	0.0000
6	2.1259	2.1284	0.0025	2.1259	2.1283	0.0024	-0.0001
	2.1259	2.1285	0.0026	2.1258	2.1280	0.0022	-0.0004

Piston Pin O.D.		inches
	Min	2.1259
	Max	2.1261
Skirt Pin Bore I.D.		
	Min	2.1281
	Max	2.1299
Clearence		
	Min	0.0020
	Max	0.0040

Average Change	
vertical	-0.0002
horizontal	-0.0002

Cummins L10-330E Engine
Installed Cylinder Liner Out-of-Round

		Before						After						Change				
cyl #		C	D	E	F	G	Taper	C	D	E	F	G	Taper	C	D	E	F	G
1	F-B	4.9214	4.9221	4.9217	4.9215	4.9215	0.0007	4.9215	4.9217	4.9213	4.9219	4.9209	0.0010	0.0001	-0.0004	-0.0004	0.0004	-0.0006
	L-R	4.9220	4.9226	4.9226	4.9224	4.9224	0.0006	4.9220	4.9231	4.9232	4.9231	4.9231	0.0012	0.0000	0.0005	0.0006	0.0007	0.0007
	Avg	4.9217	4.9224	4.9222	4.9220	4.9220	0.0007	4.9218	4.9224	4.9223	4.9225	4.9220	0.0011	0.0000	0.0000	0.0001	0.0005	0.0000
	O-of-R	0.0006	0.0005	0.0009	0.0009	0.0009		0.0005	0.0014	0.0019	0.0012	0.0022						
2	F-B	4.9204	4.9216	4.9218	4.9219	4.9221	0.0017	4.9202	4.9211	4.9212	4.9211	4.9212	0.0010	-0.0002	-0.0005	-0.0006	-0.0008	-0.0009
	L-R	4.9227	4.9229	4.9223	4.9219	4.9217	0.0012	4.9202	4.9233	4.9231	4.9228	4.9226	0.0031	-0.0025	0.0004	0.0008	0.0009	0.0009
	Avg	4.9216	4.9223	4.9221	4.9219	4.9219	0.0015	4.9202	4.9222	4.9222	4.9220	4.9219	0.0020	-0.0013	-0.0000	0.0001	0.0000	-0.0000
	O-of-R	0.0023	0.0013	0.0005	0.0000	0.0004		0.0000	0.0022	0.0019	0.0017	0.0014						
3	F-B	4.9220	4.9225	4.9223	4.9225	4.9224	0.0005	4.9205	4.9214	4.9217	4.9218	4.9218	0.0013	-0.0015	-0.0011	-0.0006	-0.0007	-0.0006
	L-R	4.9220	4.9223	4.9220	4.9220	4.9221	0.0003	4.9237	4.9236	4.9229	4.9226	4.9223	0.0014	0.0017	0.0013	0.0009	0.0006	0.0002
	Avg	4.9220	4.9224	4.9222	4.9223	4.9223	0.0004	4.9221	4.9225	4.9223	4.9222	4.9221	0.0014	0.0001	0.0001	0.0001	-0.0000	-0.0002
	O-of-R	0.0000	0.0002	0.0003	0.0005	0.0003		0.0032	0.0022	0.0012	0.0008	0.0005						
4	F-B	4.9206	4.9217	4.9217	4.9217	4.9217	0.0011	4.9201	4.9211	4.9213	4.9210	4.9211	0.0012	-0.0005	-0.0006	-0.0004	-0.0007	-0.0006
	L-R	4.9228	4.9232	4.9228	4.9225	4.9224	0.0008	4.9233	4.9239	4.9237	4.9233	4.9231	0.0008	0.0005	0.0007	0.0009	0.0008	0.0007
	Avg	4.9217	4.9225	4.9223	4.9221	4.9221	0.0010	4.9217	4.9225	4.9225	4.9222	4.9221	0.0010	0.0000	0.0000	0.0002	0.0000	0.0000
	O-of-R	0.0022	0.0015	0.0011	0.0008	0.0007		0.0032	0.0028	0.0024	0.0023	0.0020						
5	F-B	4.9207	4.9217	4.9218	4.9218	4.9219	0.0012	4.9205	4.9215	4.9215	4.9214	4.9213	0.0010	-0.0002	-0.0002	-0.0003	-0.0004	-0.0006
	L-R	4.9225	4.9228	4.9225	4.9221	4.9219	0.0009	4.9227	4.9232	4.9231	4.9226	4.9226	0.0006	0.0002	0.0004	0.0006	0.0005	0.0007
	Avg	4.9216	4.9223	4.9222	4.9220	4.9219	0.0010	4.9216	4.9224	4.9223	4.9220	4.9220	0.0008	0.0000	0.0001	0.0001	0.0000	0.0000
	O-of-R	0.0018	0.0011	0.0007	0.0003	0.0000		0.0022	0.0017	0.0016	0.0012	0.0013						
6	F-B	4.9212	4.9219	4.9218	4.9217	4.9216	0.0007	4.9211	4.9214	4.9215	4.9212	4.9211	0.0004	-0.0001	-0.0005	-0.0003	-0.0005	-0.0005
	L-R	4.9224	4.9228	4.9226	4.9224	4.9224	0.0004	4.9225	4.9232	4.9232	4.9230	4.9230	0.0007	0.0001	0.0004	0.0006	0.0006	0.0006
	Avg	4.9218	4.9224	4.9222	4.9221	4.9220	0.0006	4.9218	4.9223	4.9224	4.9221	4.9221	0.0005	0.0000	-0.0000	0.0001	0.0000	0.0001
	O-of-R	0.0012	0.0009	0.0008	0.0007	0.0008		0.0014	0.0018	0.0017	0.0018	0.0019						

Cylinder Liner Out-of-Round, Inches

Max	0.004

Cylinder Liner I.D., Inches

Min	4.9213
Max	4.9238

F-B: diameter in Front to Back direction
L-R: diameter in Left to Right direction
C,D,E,F,G: locations along cylinder axis from TDC to BDC, E is location of press fit

Average Liner Bore Change

F-B	-0.0005
L-R	0.0005
Overall	0.0000

Cummins L10-330E Engine
Bearing Weights, Grams

Rod Bearings	Before	After	Change, mg	Avg. Lower	Avg. Upper
1 Lower	104.9037	104.9030	0.7	7.2	206.3
1 Upper	104.9901	104.7348	255.3	**Max. Lower**	**Max. Upper**
2 Lower	104.7412	104.7315	9.7	12.8	340.3
2 Upper	104.9110	104.7910	120.0	**Min. Lower**	**Min. Upper**
3 Lower	105.1536	105.1514	2.2	0.7	120.0
3 Upper	104.8454	104.6598	185.6		
4 Lower	104.9872	104.9767	10.5		
4 Upper	104.8353	104.6675	167.8		
5 Lower	104.8904	104.8829	7.5		
5 Upper	104.7660	104.4257	340.3		
6 Lower	104.7689	104.7561	12.8		
6 Upper	104.9446	104.7759	168.7		

Main Bearings	Before	After	Change, mg	Avg. Lower	Avg. Upper
1 Lower	209.2683	209.1991	69.2	58.4	32.1
1 Upper	193.2661	193.2520	14.1	**Max. Lower**	**Max. Upper**
2 Lower	209.7136	209.6702	43.4	78.5	48.8
2 Upper	193.7511	193.7023	48.8	**Min. Lower**	**Min. Upper**
3 Lower	209.9322	209.8630	69.2	22.7	14.1
3 Upper	193.1128	193.0867	26.1		
4 Lower	209.7441	209.7214	22.7		
4 Upper	192.9477	192.9241	23.6		
5 Lower	209.9445	209.8793	65.2		
5 Upper	193.3678	193.3448	23.0		
6 Lower	209.7224	209.6615	60.9		
6 Upper	194.2525	194.2108	41.7		
7 Lower	209.9308	209.8523	78.5		
7 Upper	193.5258	193.4787	47.1		

Cummins L10-330E Engine
Connecting Rod Bearing Journal and Bearing Shell Clearances

	Before						After				Change	
	Bearing Journals		Bearing Shells		Clearances		Bearing Shells		Clearances		Clearances	
cyl#	A	B	F	BA	Min	Max	F	BA	Min	Max	Min	Max
1	3.1102	3.1101	3.1132	3.1133	0.0030	0.0032	3.1137	3.1132	0.0030	0.0036	0.0000	0.0004
2	3.1105	3.1105	3.1139	3.1139	0.0034	0.0034	3.1138	3.1138	0.0033	0.0033	-0.0001	-0.0001
3	3.1105	3.1102	3.1130	3.1130	0.0025	0.0028	3.1335	3.1334	0.0229	0.0233	0.0204	0.0205
4	3.1104	3.1104	3.1136	3.1135	0.0031	0.0032	3.1337	3.1337	0.0233	0.0233	0.0202	0.0201
5	3.1103	3.1103	3.1139	3.1139	0.0036	0.0036	3.1339	3.1340	0.0236	0.0237	0.0200	0.0201
6	3.1101	3.1101	3.1139	3.1139	0.0038	0.0038	3.1340	3.1340	0.0239	0.0239	0.0201	0.0201

Dimensions in inches	Min	Max
Rod Bearing Journal O.D.	3.1083	3.1107
Rod Bearing Shell I.D.	3.1113	3.1166
Rod Bearing Shell to Journal Clearence	0.0006	0.0083

A = parallel to counterweights
B = perpendicular to counterweights
F = towards front of engine
BA = towards back of engine

Average Change
0.0135

Cummins L10-330E Engine

Main Bearing Journal and Bearing Shell Clearances

	Before						After				Change	
	Bearing Journals		Bearing Shells		Clearances		Bearing Shells		Clearances		Clearances	
cyl#	A	B	F	BA	Min	Max	F	BA	Min	Max	Min	Max
1	4.4893	4.4893	4.4950	4.4951	0.0057	0.0058	4.4949	4.4948	0.0055	0.0056	-0.0002	-0.0002
2	4.4896	4.4894	4.4956	4.4956	0.0060	0.0062	4.4949	4.4950	0.0053	0.0056	-0.0007	-0.0006
3	4.4890	4.4892	4.4952	4.4951	0.0059	0.0062	4.4948	4.4949	0.0056	0.0059	-0.0003	-0.0003
4	4.4897	4.4897	4.4953	4.4953	0.0056	0.0056	4.4949	4.4947	0.0050	0.0052	-0.0006	-0.0004
5	4.4890	4.4889	4.4957	4.4955	0.0065	0.0068	4.4950	4.4949	0.0059	0.0061	-0.0006	-0.0007
6	4.4889	4.4888	4.4954	4.4953	0.0064	0.0066	4.4952	4.4950	0.0061	0.0064	-0.0003	-0.0002
7	4.4891	4.4898	4.4951	4.4950	0.0052	0.0060	4.4952	4.4950	0.0052	0.0061	0.0000	0.0001

Dimensions in inches	Min	Max
Main Bearing Journal O.D.	4.4888	4.4903
Main Bearing Shell I.D.	4.4922	4.4975
Main Bearing Shell to Journal Clearence	0.0019	0.0087

A = parallel to counterweights
B = perpendicular to counterweights
F = towards front of engine
BA = towards back of engine

Average Change
-0.0004

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APG MD 21005-5071	
CDR ARO	
ATTN: AMXRO EN (D MANN)	1
RSCH TRIANGLE PK	
NC 27709-2211	
DIR	
AMC PKG STO CONT CTR	
ATTN: SDSTO TE S	1
TOBYHANNA PA 18466-5097	
CDR AEC	
ATTN: SFIM AEC ECC (T ECCLES)	1
APG MD 21010-5401	
CDR ARMY ATCOM	
ATTN: AMSAT I ME (L HEPLER)	1
AMSAT I LA (V SALISBURY)	1
AMSAT R EP (V EDWARD)	1
4300 GOODFELLOW BLVD	
ST LOUIS MO 63120-1798	
CDR AVIA APPL TECH DIR	
ATTN: AMSAT R TP (H MORROW)	1
FT EUSTIS VA 23604-5577	
CDR ARMY NRDEC	
ATTN: SATNC US (J SIEGEL)	1
SATNC UE	1
NATICK MA 01760-5018	
CDR ARMY ARDEC	
ATTN: SMCAR CC	1
SMCAR ESC S	1
PICATINNY ARSENAL NJ 07808-5000	
CDR ARMY DESCOM	
ATTN: AMSDS MN	1
AMSDS EN	1
CHAMBERSBURG PA 17201-4170	
CDR ARMY AMCCOM	
ATTN: AMSMC MA	1
ROCK ISLAND IL 61299-6000	
CDR ARMY WATERVLIET ARSN	
ATTN: SARWY RDD	1
WATERVLIET NY 12189	

DIR AMC LOG SPT ACT
ATTN: AMXLS LA 1
REDSTONE ARSENAL AL 35890-7466

CDR APC
ATTN: SATPC Q 1
SATPC QE (BLDG 85 3) 1
NEW CUMBERLAND PA 17070-5005

PETROL TEST FAC WEST 1
BLDG 247 TRACEY LOC
DDRW
P O BOX 96001
STOCKTON CA 95296-0960

CDR ARMY LEA
ATTN: LOEA PL 1
NEW CUMBERLAND PA 17070-5007

CDR ARMY TECOM
ATTN: AMSTE TA R 1
AMSTE TC D 1
AMSTE EQ 1
APG MD 21005-5006

PROG MGR PETROL WATER LOG
ATTN: AMCPM PWL 1
4300 GOODFELLOW BLVD
ST LOUIS MO 63120-1798

PROG MGM MOBILE ELEC PWR
ATTN: AMCPM MEP 1
7798 CISSNA RD STE 200
SPRINGFIELD VA 22150-3199

CDR
ARMY COLD REGION TEST CTR
ATTN: STECR TM 1
STECR LG 1
APO AP 96508-7850

CDR
ARMY BIOMED RSCH DEV LAB
ATTN: SGRD UBZ A 1
FT DETRICK MD 21702-5010

CDR FORSCOM
ATTN: AFLG TRS 1
FT MCPHERSON GA 30330-6000

CDR TRADOC
ATTN: ATCD SL 5 1
INGALLS RD BLDG 163
FT MONROE VA 23651-5194

CDR ARMY ARMOR CTR
ATTN: ATSB CD ML 1
ATSB TSM T 1
FT KNOX KY 40121-5000

CDR ARMY QM SCHOOL
ATTN: ATSM CD 1
ATSM PWD 1
FT LEE VA 23001-5000

ARMY COMBINED ARMS SPT CMD
ATTN: ATCL CD 1
ATCL MS 1
FT LEE VA 23801-6000

CDR ARMY FIELD ARTY SCH
ATTN: ATSF CD 1
FT SILL OK 73503

CDR ARMY TRANS SCHOOL
ATTN: ATSP CD MS 1
FT EUSTIS VA 23604-5000

CDR ARMY INF SCHOOL
ATTN: ATSH CD 1
ATSH AT 1
FT BENNING GA 31905-5000

CDR ARMY AVIA CTR
ATTN: ATZQ DOL M 1
ATZQ DI 1
FT RUCKER AL 36362-5115

CDR ARMY CACDA
ATTN: ATZL CD 1
FT LEAVENWORTH KA 66027-5300

CDR ARMY ENGR SCHOOL
ATTN: ATSE CD 1
FT LEONARD WOOD
MO 65473-5000

CDR ARMY ORDN CTR
ATTN: ATSL CD CS 1
APG MD 21005

CDR ARMY SAFETY CTR
ATTN: CSSC PMG 1
CSSC SPS 1
FT RUCKER AL 36362-5363

CDR ARMY CSTA
ATTN: STECS EN 1
STECS LI 1
STECS AE 1
STECS AA 1
APG MD 21005-5059

CDR ARMY YPG
ATTN: STEYP MT TL M 1
YUMA AZ 85365-9130

CDR ARMY CERL
ATTN: CECER EN 1
P O BOX 9005
CHAMPAIGN IL 61826-9005

DIR 1
AMC FAST PROGRAM
10101 GRIDLEY RD STE 104
FT BELVOIR VA 22060-5818

CDR I CORPS AND FT LEWIS
ATTN: AFZH CSS 1
FT LEWIS WA 98433-5000

CDR
RED RIVER ARMY DEPOT
ATTN: SDSRR M 1
SDSRR Q 1
TEXARKANA TX 75501-5000

PS MAGAZINE DIV
ATTN: AMXLS PS 1
DIR LOGSA
REDSTONE ARSENAL AL 35898-7466

CDR 6TH ID (L)
ATTN: APUR LG M 1
1060 GAFFNEY RD
FT WAINWRIGHT AK 99703

Department of the Navy

DIR LOGISTICS PLANS & POLICY/
STRATEGIC SEALIFT PROG DIV (N42)
ATTN: N420 1
2000 NAVY PENTAGON
WASHINGTON DC 20350-2000

CDR
NAVAL SEA SYSTEMS CMD
ATTN: SEA 03M3 1
2531 JEFFERSON DAVIS HWY
ARLINGTON VA 22242-5160

CDR
NAVAL SURFACE WARFARE CTR
ATTN: CODE 63 1
CODE 632 1
CODE 859 1
3A LEGGETT CIRCLE
ANNAPOLIS MD 21402-5067

CDR
NAVAL RSCH LABORATORY
ATTN: CODE 6181 1
WASHINGTON DC 20375-5342

CDR
NAVAL AIR WARFARE CTR
ATTN: CODE PE33 AJD 1
P O BOX 7176
TRENTON NJ 08628-0176

CDR 1
NAVAL PETROLEUM OFFICE
CAMERON STA T 40
5010 DUKE STREET
ALEXANDRIA VA 22304-6180

OFC ASST SEC NAVY (I & E) 1
CRYSTAL PLAZA 5
2211 JEFFERSON DAVIS HWY
ARLINGTON VA 22244-5110

CDR
NAVAL AIR SYSTEMS CMD
ATTN: AIR 53623C 1
1421 JEFFERSON DAVIS HWY
ARLINGTON VA 22243-5360

Department of the Navy/U.S. Marine Corps

HQ USMC
ATTN: LPP 1
WASHINGTON DC 20380-0001

PROG MGR COMBAT SER SPT 1
MARINE CORPS SYS CMD
2033 BARNETT AVE STE 315
QUANTICO VA 22134-5080

PROG MGR GROUND WEAPONS 1
MARINE CORPS SYS CMD
2033 BARNETT AVE
QUANTICO VA 22134-5080

PROG MGR ENGR SYS 1
MARINE CORPS SYS CMD
2033 BARNETT AVE
QUANTICO VA 22134-5080

CDR
MARINE CORPS SYS CMD
ATTN: SSE 1
2030 BARNETT AVE STE 315
QUANTICO VA 22134-5010

CDR
BLOUNT ISLAND CMD
ATTN: CODE 922/1 1
5880 CHANNEL VIEW BLVD
JACKSONVILLE FL 32226-3404

CDR
MARINE CORPS LOGISTICS BA
ATTN: CODE 837 1
814 RADFORD BLVD
ALBANY GA 31704-1128

CDR 1
2ND MARINE DIV
PSC BOX 20090
CAMP LEJEUNNE NC 28542-0090

CDR 1
1ST MARINE DIV
CAMP PENDLETON CA 92055-5702

CDR 1
FMFPAC G4
BOX 64118
CAMP H M SMITH HI 96861-4118

Department of the Air Force

HQ USAF/LGSSF
ATTN: FUELS POLICY 1
1030 AIR FORCE PENTAGON
WASHINGTON DC 20330-1030

HQ USAF/LGTV
ATTN: VEH EQUIP/FACILITY 1
1030 AIR FORCE PENTAGON
WASHINGTON DC 20330-1030

AIR FORCE WRIGHT LAB
ATTN: WL/POS 1
WL/POSF 1
WL/POSL 1
1790 LOOP RD N
WRIGHT PATTERSON AFB
OH 45433-7103

AIR FORCE WRIGHT LAB
ATTN: WL/MLBT 1
2941 P ST STE 1
WRIGHT PATTERSON AFB
OH 45433-7750

AIR FORCE WRIGHT LAB
ATTN: WL/MLSE 1
2179 12TH ST STE 1
WRIGHT PATTERSON AFB
OH 45433-7718

AIR FORCE MEEP MGMT OFC 1
615 SMSQ/LGTV MEEP
201 BISCAYNE DR STE 2
ENGLIN AFB FL 32542-5303

SA ALC/SFT 1
1014 BILLY MITCHELL BLVD STE 1
KELLY AFB TX 78241-5603

WR ALC/LVRS 1
225 OCMULGEE CT
ROBINS AFB
GA 31098-1647

Other Federal Agencies

NASA LEWIS RESEARCH CENTER CLEVELAND OH 44135	1	DOE CE 151 (MR RUSSELL) 1000 INDEPENDENCE AVE SW WASHINGTON DC 20585	1
NIPER PO BOX 2128 BARTLESVILLE OK 74005	1	EPA AIR POLLUTION CONTROL 2565 PLYMOUTH RD ANN ARBOR MI 48105	1
DOT FAA AWS 110 800 INDEPENDENCE AVE SW WASHINGTON DC 20590	1		